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VOLUME 2

METHODS

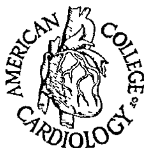
CARDIOLOGY

An Encyclopedia of the Cardiovascular System

SPONSORED BY THE AMERICAN COLLEGE OF CARDIOLOGY

EDITED BY ALDO A. LUISADA, *M.D.*

FOREWORD BY ASHTON GRAYBIEL, *M.D.*



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CARDIOLOGY

An Encyclopedia of the Cardiovascular System

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Foreword

This work is at once a landmark in clinical cardiology and an indication of the Golden Age of Medicine in which we now live. Because wondrous things have become commonplace, we can appreciate this age only in retrospect. From rude beginnings it is possible to trace, over the centuries of recorded history, the gradual refinement in skills, the slow accumulation of factual knowledge, and the emergence of a scientific discipline so essential to success in the walks of science. Progress, painfully slow and often faltering till late in the nineteenth century, then began to accelerate at an ever-increasing rate. Within the memory of some now living, individual triumphs in scattered departments of science combined in one mighty triumphant flourish to usher in the modern era Epidemics, once the scourge of man, were abolished; certain diseases, once relentless in their course, were controlled, old age, once a rarity, became the rule. It is unlikely that within a comparable period of time man will ever again repeat the stupendous feat of doubling his span of life.

Cardiologists, while sharing in these triumphs, saw heart disease assume the lead as a cause of death in many countries Thus, although gratified by the increased longevity of man, we are nevertheless challenged by the disclosure that the cardiovascular system is now the weakest strand in the thread of life. Indeed, its relative importance in the lives of men appears destined to increase, for there is nothing in sight pointing to a major break-through in the prevention of heart disease in old age.

In sponsoring this encyclopedia, the American College of Cardiology, dedicated to the continuing education of its membership, is simply fulfilling one of its obligations That this particular obligation weighed more heavily on the minds of some of its officers than on others raised the question of the relative merits of different methods of postgraduate education We cannot here record the deliberations which finally led to approval of this undertaking, but they reflected the need for putting on record the widening horizons of our knowledge of cardiovascular disease.

That the presentation of information concerning the heart and circulation requires four volumes involving upwards of 250 authors has important implications. It is evidence that narrowing of *interest* and progress go hand in hand, and that subdivision within the field of cardiology is well established. But this subdivision, so essential for progress, must be reconstituted for those whose clinical responsibilities cover a broad area. In effect this encyclopedia represents such a reconstitution It contains authoritative information abstracted from an immense mass of medical literature which could not be reviewed effectively by an individual. The organization of this material is based on a logical framework

Preface

This work was started as a result of a bold and far-sighted initiative of Dr. Ashton Graybiel, then president of the American College of Cardiology.

The task of editing an encyclopedia of cardiology represents a challenge which is both appealing and frightening.

Among the multitude of books of cardiology which have been published in the last 20 years, the majority belongs to the type of the medium-sized, monographic textbook written by a single author. A few have been written in collaboration by several authors. These, however, do not attempt to be complete and are, moreover, too unsystematic to be helpful. Being of the "fixed-volume" type, they are soon outdated and, therefore, forgotten.

In ancient Greece, *encyclopaedia* meant "instruction in the whole circle, or complete system of learning." In a more restricted sense, encyclopedia means "a system or classification of various branches of knowledge; a subject on which many books have been published." While many encyclopedias of the past have been of the "alphabetical type" (each word to be explained is listed in alphabetical order), others have tried to reconcile system with completeness. Thus, even in the early editions of the *Encyclopaedia Britannica,* the various sciences and arts (such as anatomy or surgery) were "digested into distinct treatises or systems." On the other hand, technical terms were explained in alphabetical order. Older encyclopedias, like Plinius's *Natural History* of the year 77 A.D. (37 books with 2,493 chapters) or *Yung-Lo Ta Tien,* the Chinese encyclopedia of 1403 A.D. (11,095 volumes prepared in four years by over 2,000 scholars), were developed according to system. The latter even included well-known books reproduced without change.

In the opinion of the editor, a modern encyclopedia of cardiology ought to have the following characteristics: (1) It should encompass all available knowledge on the heart and vessels, including history, embryology, anatomy, physiology, physical and technical methods of examination, bacteriology and pathology, clinical sciences, surgery, pharmacology and therapy, rehabilitation, and the various "allied fields." (2) It should present them in a systematic order, thus permitting easy consultation. (3) It should be of the loose-leaf type, in order to keep abreast of medical progress. It is then possible that some of the readers may prefer to call this a *treatise.*

The principle of extending the work to all kinds of knowledge in the cardiovascular field should not be carried too far in the marginal fringes of medical or technical sciences. This process would divert and distract the attention of the reader and would render consultation too difficult. Therefore, a process of selection and limitation is an important part in the preparation of an encyclopedia of

which constitutes a resynthesis of the important elements in the field of cardiology.

In using this encyclopedia, the physician must let go of his inclination to be taught, and cultivate the art of selecting new items of information and fitting them into a frame of reference dictated by his needs. This method does require a capacity for mental independence and is effective only in so far as this is exhibited by those for whom the encyclopedia is intended. Admittedly a work of this sort represents a form of communication in which there is much redundancy. At what point will the evil of redundancy equal or exceed the good contained in the message? Herein lies a very real problem with which we should be concerned in the future.

It is noteworthy that in the compilation of this work we are more dependent upon an editor than upon an author. The choice of Dr. Luisada to edit the work has been fortunate. He has exhibited not only a natural talent for this task but also the quality of persevering in the face of difficulties. To him alone belongs the credit for bringing the encyclopedia to fruition. The present handbook must be regarded as a monument to his genius.

ASHTON GRAYBIEL

2. Selection of persons with diversified knowledge (physiology, pathology, pediatrics, surgery, etc.), so that all fields may be covered by competent editors.

3. Choice of as many young scientists as possible, in order to have a high potential of enthusiasm, criticism, and working capacity.

The final product will reveal whether these directives are sound and have been followed as closely as possible.

The publication of this encyclopedia was made possible by the continued support of the American College of Cardiology through the action of its board of trustees, by generous contributions of five pharmaceutical houses, and by the warm collaboration of the McGraw-Hill Book Company, Inc., Blakiston Division.

ALDO A. LUISADA
Editor in Chief

cardiology. It is likely that a four-volume, 5,000-page encyclopedia would represent the optimal size. However, practical considerations indicate a more limited approach for the first version. Therefore, a four-volume, 3,600-page size is considered for the first edition, even though gradual revision and extension over the following ten years will probably increase the size to that previously mentioned.

Several titles have been considered for this encyclopedia. The one preferred by the editor, *Encyclopedia of Cardiology*, has been discarded for fear of discouraging prospective readers. The more modest title which has been selected—*Cardiology*—emphasizes the main scope [knowledge about the heart (and vessels)] even though it has a more modest sound than the original title. The titles of the four volumes have been selected on the basis of their content.

The problem of correlation has been the rock on which many textbooks written by multiple authors have foundered. If the various parts do not follow a logical sequence, if some of them are disproportionately long or short; if some are written by obscure authors of poor talent while others are the result of the work of well-known authorities, then the whole encyclopedia has no value.

In order to obviate these possibilities, the following steps are necessary: (1) the authors selected should be among the best, (2) each should receive a carefully selected and clearly outlined job, and (3) the editors should be able to refuse, abbreviate, or send back for correction any received text. Therefore, courage, patience, and hard labor are necessary to ensure a successful literary production.

The outcome of the work depends to a large extent upon the selection of authors Well-known authors who have left a mark in the history of cardiology are the natural choice. However, they may be reluctant to undertake a major task and, moreover, may not be able to ensure continuity on account of their age. A compromise may be represented by asking these authors to prepare the text in collaboration with one of their associates The associate would be the natural choice for any future revision of the text. However, a different author may entirely revise a chapter at a future date

Science is international. If a truly objective work is to be published, authors of all nationalities should be asked to contribute The recent tremendous progress of cardiology in the North American continent may require that a majority of the authors be selected in the United States and Canada However, numerous contributors have been selected from England, continental Europe, Mexico, South America, Africa, and Asia, so that a truly "global" representation of cardiology may result.

How much of the text should reflect generally accepted viewpoints, how much should present new ideas still awaiting confirmation? This problem cannot be solved in a general way. The viewpoint of the editor is that an intermediate position should be preferred Texts reflecting only generally accepted views might render the entire work obsolete within a few years On the other hand, many new viewpoints cannot withstand the test of time and are gradually discarded. Whatever the error, whether in the sense of conservatism or in that of progressivism, a loose-leaf type of work may remedy it more rapidly than any standard type of volume.

The Editorial Board has been selected with great care according to these viewpoints:

1. Inclusion of a few authorities which would help in laying down the directives of the work.

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PART 3

Examination by means of the senses and related technical aids

1

Psychological implications of the medical interview

FRED P. ROBBINS

INTRODUCTION

The interview is one of the chief contributions of modern dynamic psychiatry to medicine In the treatment situation, the physician attempts to establish an interpersonal relationship between the patient and himself. The model for this relationship is instituted in the initial interviews. For this reason, the word "interview" has been substituted for "history taking." The interviewer has definite goals in mind which he hopes to accomplish most effectively in the smallest period of time

Early in his training the medical student is indoctrinated in procedures to be used in order to understand the history of the patient's illness. This is essentially a part of the total approach designed to make a diagnosis and is designated as "the medical history" In the past, the history of the present illness and past illnesses was elicited, but the personal history of the patient was omitted This is now being remedied and special attention is paid to the emotional problems of the patient. In the course of his training, the medical student learns the general problems of the different specialties, and is able to treat some of these disorders If the disease requires that a specialist be called in, he knows at which point this should be done.

The specialist, too, must be aware of some of the manifestations of diseases not strictly in his special field and in some cases may treat those which are of a less complicated nature. Modern technique requires that the medical history include questions which should give the physician an insight into the patient as someone who harbors an illness but is at the same time a living, breathing, fearing human being.

SOME BASIC PRINCIPLES

A skillful interviewer recognizes that a comprehensive approach includes not only the injuring agent but the characteristics of the host He also assumes the possibility of a multicausal etiology of disease. Asthma may have a combination of allergic, emotional, and infectious causes responsible for repeated attacks.

There is always *an emotional reaction to disease*, whether or not emotional factors were prominent in its causation. This response of the organism to stress includes a psychological response, even though the injuring agent may be degenerative or infectious This emotional response is often the very thing that interferes with adequate history taking For example, it is common for patients with severe coronary thrombosis to tend to minimize their attacks, while patients with cardiac neurosis often maximize their attacks and are most anxious to gain hospitalization.

Dynamic psychiatry has made physicians increasingly aware of the fact that history taking and mental examination cannot be divorced. While giving his history, the patient is also revealing his mental and emotional attitudes, and the alert physician is observing the patient's

a sincere, wholehearted interest in him and to avoid giving *him the feeling* that the therapist is acquiring *routine information*. The less experienced the physician, the more anxious will he be to get the required facts in the proper *order*. The chief factor in unsuccessful initial contact with the patient seems to be the doctor's insincerity expressing itself in a desire for a rapid formal work-up (which often enough is prescribed by hospital or clinic). Awareness of the emotional needs of the patient and of his strengths and weaknesses, as the doctor senses them, rather than an interest in completing a routine schedule of predetermined questions, determines the attitudes in the doctor to which the patient can most readily respond

In the interview the doctor will find himself responding with certain emotional reactions to the patient This is information which is subtle and involves the personal equation to a high degree The personal interaction between the examiner and examinee constitutes the most vital part of this examination. The examiner must not only participate in the interview, but must be an *observer at the same* time. The emotional responses of the physician are the results of the patient's characteristic mode of behavior and are made more obvious in situations of stress These are important clues which, if understood and used correctly, can help the physician in establishing an effective relationship with the patient For example, a *physician* may find himself reacting with annoyance to the patient's avoidance of the seriousness of his disease The annoyance could easily spring from the frustration the doctor *feels in the fact* that the patient is minimizing his need *for the* doctor's help This could easily be the type of person who has placed an inordinate *premium* on "independence" A few words by *the physician* which would indicate an awareness of *this* fact as well as an awareness of the fact that the patient may be anxious about the *disease process could* easily change the character of the entire interview. This awareness of the patient's intent by examining one's own reaction *requires a minimum of* preoccupation and prejudice to the *observation* and assessment of data obtained. Some physicians are able to acquire *this after* some time and experience.

Apart from certain areas in which the physician may be uncertain about *his* responses and reactions, mulling over his own *responses* is a fairly good yardstick for evaluating the appropriateness of the patient's responses He (the physician) has the advantage of carrying around with him at all times an appropriate accurate standard of measuring behavior. Thus, if a patient tells a story of having a fight with his boss because his boss had criticized him, the physician tries to understand how he would have reacted in a similar situation. Actually, he tries to measure whether the patient under- or overreacted to the boss or whether his response could have been reasonable. Here the response is not directly to the patient, but rather to the situation described *by him, and* therefore less likely to lead to specific reactions by the physician. However, here, too, there are some pitfalls. It becomes necessary for the physician to understand where *his own responses* deviate from the usually accepted *"norms" of behavior* If he has a tendency to feel that doctors make very few mistakes, he will be very critical of patients who complain about their local physicians and miss realistic bases of complaints that the patient may have.

WHAT INFORMATION SHOULD BE ELICITED

Since the disease may be the result of emotional problems or the reaction to illness may result in an emotional reaction, the precipitating circumstances of the illness deserve special attention. The universal aim of the first interview *is to* elucidate the presenting problem Most often, the setting of the initial onset *of the* illness is the critical period which *reveals* most of the associated causative factors of the patient's illness Suppose a patient had her *first acute* colitis attack on her first important date. Some subsequent attacks would also be *precipitated* in similar situations but more often would be attributed to some *dietary indiscretion* The first attack suggested that the emotional problem has to be considered as a *factor in the* total management. On the other hand, the *patient's* subsequent reaction to the onset of the disease can give valuable information concerning *the patient's* attitude toward it. Some patients have a tendency to exploit *disease*, using it as a lever to gain attention from family and friends, others may go from doctor *to doctor in an attempt* to get a special and perhaps "magical" cure; and still others may

mental status in whatever he is saying or doing. There is the recognition that treatment does not start only after the careful formulation of the diagnosis History taking, examination, and treatment all take place concomitantly, whether the physician wills it or not. Lastly, there is the growing awareness of the significance of the patient-doctor relationship (rapport) as the very framework within which the nature and the meaning of the patient's productions must be understood. The old family physician's "stock in trade" was an intuitive grasp of this relationship which he artfully put to use as an adjunct to his prescriptions in order to help cure the patient.

THE PHYSICAL AND SOCIAL SETTING OF THE INTERVIEW

To describe the physical setting of the interview may seem to be stressing unimportant details. However, an interview may fail completely if other patients are present, for the patient feels he may be overheard Frequent interruptions often undermine the effectiveness of the interview, for the patient can easily react by feeling that the doctor is preoccupied with other problems, and that his (the patient's) problems are of relative inconsequence to the doctor The physician should see the patient alone, in surroundings comfortable to the patient He should take the initiative in putting the patient at ease, both physically and emotionally.

To help establish the social setting, the physician should be in tune with the patient's mood He should speak quietly and naturally, avoiding banalities. The patient should not be met with superficial nonsense and false heartiness Greeting the patient by name is an obvious and yet important method of establishing initial contact and of relieving the patient of the almost universal anxiety that the doctor might be confusing his case with that of someone else.

The basic approach must be respect for another human being and his dignity This emphasis on respect is almost a cliché in the teaching of the art of medicine, but it is interesting to speculate that the modern physician has rights and privileges in the investigation of his patient far beyond that which any kings and popes had of their subjects Not only may he ask the patient to disrobe, but he may inspect and peer at the patient's entire body. He may percuss the chest, palpate the abdomen, and pass all sorts of tubes into the body orifices He may ask questions concerning the most intimate details of the patient's life—material to which the biographer or historian cannot possibly gain access and which the person would never relate to any other human being.

ELICITING INFORMATION

The foregoing has been an attempt to describe some basic principles as well as a setting which would be most helpful in reaching the goal of the diagnostic interview—eliciting the maximum amount of information in the time available to the physician.

At the beginning of the interview, it is well to let the patient talk about what seems most important to him After a few minutes of this, it is usually a simple matter to change the subject, if necessary. That is, the examiner should allow the talkative patient to take the lead if necessary, but should himself take the lead if the patient finds it difficult to communicate The inquisitory technique is an attempt on the part of the physician to maintain his equilibrium by maintaining his superiority. The beginner is particularly vulnerable in that, more often than not, he is in secret agreement with his patient who says, "But what can you do for me, Doctor, just by talking?" There is a certain defensiveness about the fact that one of our most important tools is communication. Freud stated, " words, however, are surely not to be looked down upon Words, after all, are a powerful instrument, the means by which we express our feelings towards each other, the agent through which we influence one another Words are liable to benefit us in the extreme or liable to hurt us to the quick."

The physician should proceed from the known to the unknown, delaying searching questions until rapport has been established. It is important for patients to know that the interviewer is on their side, they do not know this at first Expressions such as, "I know what you mean," or, "That's interesting. Could you elaborate?" are good catalytic agents. When the patient thinks of the doctor as a therapist rather than a gatherer of information, a real interchange of understanding and feeling develops It is necessary to impart to the patient

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2

The clinical history

SALVADOR ACEVES

GENERAL PRINCIPLES

The prime importance of the clinical history is obvious. It constitutes the necessary material for the diagnosis which, together with the treatment, is the essential function of the clinician The treatment depends upon the diagnosis, and this will always be incomplete or inaccurate without the necessary collection of those data which report all the previous events. It is not exaggerated to say that *the clinical history is the most important part of the general examination of a patient* and constitutes for the doctor a real proof of his capacity as a clinician To take a good history requires special skill, knowledge, and experience.

In the history, all data useful for the diagnosis should be reported in succession and in order of importance No pertinent facts should be omitted The tendency not to omit anything could be interpreted as the desire to write an extensive and ponderous text, this is not so. However, it is best to take notes during the conversation with the patient and then to write a short history, which should neither omit important facts nor include too many This can be done only with a remarkable *capacity for synthesis*, which is difficult to acquire, and an *aptitude for clear writing*, which is also uncommon The capacity for synthesis should be coupled with *medical experience* based on training and emotional maturity attained through constant dealing with patients It reveals sympathy for people and the ability to understand their problems with a desire to offer help When these qualities are present, a doctor is able to write a good clinical history.

Besides this important role in the solution of the individual problem of each case, the history has a role of general order. It constitutes the foundation of the clinical investigation. Taking histories with well-collected, well-analyzed, and well-recorded data is in fact the basis of an investigation which will eventually advance the knowledge of medicine in some of its fields. Every time one reviews a clinical history and compares the data with those which are contained in the autopsy findings, one regrets that some facts which could have been of great interest were not recorded

In the clinical discussion of a case, there never is difficulty because of abundance of data On the other hand, many times one may be embarrassed by not having on hand some important facts of the history. The same thing may occur in the revision of autopsy material for the purpose of investigation.

The "clinical chart" is composed of *the anamnesis*, present symptoms, and physical examination In this chapter the term "history" will be used in reference to that part of the clinical study which is obtained through interrogation.

There are two basically opposite types of clinical history In one, each question is followed by a blank space where one writes *yes* or *no* (or a plus or minus sign), or a space where one writes in ciphers an estimate of the positive answer This type of history, *taken on the basis of a series of prepared questions*, is easier to take and to copy, but leaves the patient with an unfavorable and disillusioned idea of the study to which he has been submitted.

need to deny the existence of disease, waiting for a long time before finally seeking help. These reactions, and many others, serve as important clues for understanding the person's reaction to disease, and determine the future course of treatment.

In general, interest is centered in two large categories in the patient's life: the external and internal. By the former is meant his moods, doubts, conflicts, aspirations, ideals, view of self, and so on. These are the areas which can be best explored by the physician. The latter are areas of activity which are usually unconscious and belong in the domain of the psychiatrist. The external aspects of the patient's life are observable in his total behavior in various situations, in his relationship to other human beings under more or less stress. From these data one either intuitively or logically forms an opinion as to patterns of behavior from which one hypothesizes what prior somatic or psychological experiences were significant and relatable to the present life problem. A patient whose father has died of coronary thrombosis and whose mother suffers from hypertension would be expected to react more intensely to precordial pain than would a person without this history. This could be even more significant if the precordial pain started at the time of the father's death, and the patient described other events which indicated the close identification between father and son.

As a result of the data given confidentially to a trusted physician, the patient will have given a good picture of his life. In addition, the examiner will have a rather complete account of the intellectual, affective, and interpersonal context in which the answers were given. The over-all picture, as finally attained, should have told him the patient's methods of dealing with people, their methods of dealing with him, the usual methods with which he copes with his environment, the responses that he expects, his reaction to frustration, his strengths and weaknesses in relation to others, and the repetitious nature of these patterns.

The general practitioner or family doctor knew a great deal about the inner attitudes, the personality, and the environment of his patients. He was able to recognize total life situations and interpersonal responses, but he did so only in an intuitive way, for he could not formulate what he knew and did. However, he used these tools in order to promote a doctor-patient relationship called "rapport." This was designed to give the patient confidence in the physician's ability which allowed the physician to extract the greatest amount from his therapeutic armamentarium. The behavioral sciences have confiscated these empirical data and are now returning them to the doctor in the scientific language of comprehensive medicine. Put into operation, in actual work with patients, these cold facts cannot substitute for warm human understanding and intuitive grasp of the feelings of people in trouble.

SUMMARY

The diagnostic interview is the beginning of the establishment of the doctor-patient relationship and as such represents the start of therapy. Skillful interviewing requires the blend of medical information, the knowledge about people, and the art of interpersonal relations. Much of significance may be obtained in the context of the medical history and during the process of physical examination. The actual and specific methods used cannot be prescribed. General principles have been discussed, but in the last analysis, it must be recognized that each patient is a person who behaves in his own way, and that every doctor has his own specific approach to the interpersonal relationship. No two interviews are alike. The physician uses those tools with which he is most adept. As long as the general principles are adhered to, and the doctor exerts a sincere effort in attempting to improve his understanding of his patient, there must develop a mutual reaction which will inevitably benefit both participants. With time, a good physician compares past experiences with the present one, draws his conclusions, and finds that his sensitivity becomes heightened and grows greater with experience.

nosis depends to a large extent upon the ability with which the facts of the interrogation (including the evaluation of the symptoms) have been recorded, weighed, and analyzed. "The patient and his family," says Mackenzie, "frequently are indifferent to the diagnosis, but are deeply interested in the prognosis, that is to say, in the presence or absence of danger"

Knowing that a well-conducted interrogation can give all this and more, and realizing that this part of the clinical study may cause the loss of important data if performed without skill, some eminent cardiologists prefer not to leave this part of the examination to young assistants On the other hand, the physical examination loses less of its value if it is left to an assistant.

In a hospital, after a case has been described, it is always useful to have at least a brief conversation with the patient, going over with him the most important symptoms and, at times, doubtful points Important data can be obtained from this direct contact, however brief, either about the findings themselves or in regard to the emotional level of the patient. This personal contact should be made without rushing, without rigid reserve, and with interested sympathy It is fundamental to realize that one is not only dealing with diseases but with a patient, with a personality having problems and specific affective peculiarities *There are few things which are more important than the establishment of this relationship between doctor and patient* In particular, the good result of the treatment may hinge upon the confidence that the patient places in his doctor. Either this confidence is obtained during the interrogation, or not at all, and then one of the important elements of treatment is lost.

PROCEDURE

The elaboration of the clinical history is composed of these stages (1) the collection of data, (2) their evaluation and organization in order of importance, and (3) their transcription in the protocol These stages are actually different While the collecting of data should be started at the onset of the symptoms which constitute the present complaints, the written history should be taken in the opposite form, namely, chronologically. It is natural, in reading a protocol, to start with past events, like the *hereditary data, family environment*, information relative to *habits, customs*, and *hygiene*, and *past diseases* When the proper background is obtained, the patient's narration can actually be reported so that it can be used to maximum advantage. It may be inadvisable and occasionally impossible, when a patient has present complaints which are a cause of worry and represent the reason of his consultation, to start the interview with questions referring to diseases suffered in the past by his parents and grandparents. After the necessary time has been dedicated to the analysis of the present complaints and the subject is closed, the patient will find it natural to answer questions dealing with data referring to past diseases, his family, his habits, and so forth

General Inspection. In the first contact with the patient, before talking to him, one should observe with great attention his *facies, appearance*, movements, behavior, and emotional reactions Note will be taken also of some physical signs such as dyspnea, jaundice, venous engorgement, pallor or cyanosis, edema, and paralysis of one of the extremities All these facts, which are collected by a skillful physician at the first glance, may constitute a wonderful preliminary to the beginning of the interview. During the interrogation, observation of the patient should be continued, so that the initial observations will be sharpened, enriched, and confirmed or modified.

How to Begin. One natural and productive way to start the interrogation is at the initial date of the complaints. The answer to this question will give an idea about the picture which will be found if it is acute or chronic, if its evolution has been slow or rapid One more question should try to confirm the precise date of the *onset*. Was there any complaint before the date which has been given as the beginning of the disease? *It is frequent that the date given as the beginning of disease corresponds actually to a stage of flare-up and not to the real beginning of the symptoms* The suggested question may clear up this point.

Facts Supplied Spontaneously. Once the onset has been definitely established, the patient will be asked about *his present complaint*. The attention will be concentrated on the patient's own explanation, which he should be allowed to develop freely. The patient may be a good observer, a man of good emotional stability,

Although it may contain all the desirable data for the clinician, it is a document without personality, is not specific, and has little value for the diagnosis. *The diagnosis is a conclusion that cannot be reached only with plus and minus signs, even though it is based on a great number of them.* It is possible that this type of history will be easily handled in the course of generic investigations based on the review of many protocols for special types of surveys. But for a particular patient, it gives unsatisfactory results.

The other extreme is *the history taken without limitations.* This history can give a good idea of the clinical problem but its handling and utilization in later investigation make it laborious and difficult

A good middle method is best. This is a history in which the patient's answers are not enclosed by rigid and obligatory boundaries but in which there are a few printed headings, which will never be omitted, and there is a place where the answers of the patient can be written in detail

The "history" blanks of the *Institute of Cardiology of Mexico* have in their margins a series of indications which only serve as reminders for physicians in training, so that they record data which should never be omitted and try to obtain them from the patient if they have not been volunteered. It should be pointed out that absence of these data is often useful for the diagnosis as *a negative fact* It is self-evident that a negative fact will never be recorded as such if the corresponding question has not been asked

DEFINITION

The clinical history is the narration and description which is given by the patient of his symptoms, grievances, and experiences in relation to his disease. These are presented in an orderly fashion and in a definite form for the use of the physician The history is composed of the narration and the written record There are diseases and functional disturbances of the heart in which identification is made only through questioning, and in which other methods of exploration will hardly be able to reach a probable diagnosis. One instance is angina pectoris. There are also cardiac disturbances in which the patient's statements may give a definite idea about the probable cause but need to be integrated by the data of physical examination. Among them are heart failure, peripheral vascular failure, and paroxysmal tachycardia.

CLINICAL VALUE

It is generally accepted that the narration of history given by the patient has a clinical value of prime importance. The study of the patient through his history is difficult, but useful and fascinating. The interrogation often deals with subjective phenomena; with them are recorded both *the symptoms* of the disease and *their repercussions upon the psyche of the patient.*

The *emotional reaction* of the patient to his symptoms and his reaction to the daily stimuli while being oppressed by these symptoms make at times a complex picture. This may also be complicated by familial and hereditary elements, which may be relevant in regard to the disease.

The recording of the data obtained through questioning, their study, and their interpretation, represent a fascinating exercise which is usually rewarding One difficulty lies in the fact that *the clinician has at his disposal only those elements which the patient is willing to supply* Even when full cooperation is obtained, the keenness of observation of the patient, his capacity of description, his intelligence, the interpretation which he gives to his symptoms, even his likes and dislikes, introduce factors of uncertainty for the clinician Precision and accuracy in the unsafe ground of subjective symptoms is obtained only under the guidance of a clinician who has experience, intelligence, and skill. It is in the handling of these fluctuating elements of the diagnosis that the difference between a beginner and one who has spent many years in daily dealings with patients can be appreciated Only an experienced physician is able to grasp the nuances of feeling and the exact value of a symptom He can refuse to accept a fact without significance, or, on the contrary, persist in questioning about a relevant one until full information is supplied.

A complete interrogation can also contribute to the prognosis The *prognosis* in medicine is always so uncertain and unpredictable that it constitutes the most difficult exercise among the functions of a physician This is certainly true in the field of cardiovascular diseases The possibility of formulating a prog-

and edema After a meticulous identification of the symptoms, dyspnea will be selected as the most important item. It should be identified, analyzed, and interpreted in every one of its characters The clinician should investigate the existence of every one of its varieties; he should analyze its different forms and the conditions under which it appeared and observe its evolution Then he may reach the conclusion that it is a genuine dyspnea due to heart failure and try to correlate it with other possible symptoms of heart failure. Finally, with direct questions, he should try to see whether some of the missing data may still be recognized, so that the syndrome of heart failure is definitely confirmed: for example, evidence of pulmonary congestion (beside the dyspnea), renal and hepatic congestion, cerebral congestion, and so on

It is possible that, when the existence of cardiac failure is definitely established, a vascular syndrome or the symptoms of hypertension will also be found. The latter may be responsible for the heart failure or may be an additional syndrome

Although "integration" of a syndrome constitutes the natural follow-up of an interrogation in order to reach a diagnosis, sometimes the interrogation leads to it without further stages. This is clear when the diagnosis of rheumatic fever is obtained through simple interrogation

One thing which is always of capital importance is the careful study of the evolution of symptoms

Clinical Entities Associated with the Chief Complaint. In order to have a diagnosis which is as complete as possible, a line of questioning dealing with other systems should also be used This additional knowledge is a necessary complement which may reveal evidence of visceral congestion caused by heart failure. In this way, moreover, symptoms of possible concomitant diseases, of which there has been no mention, can be collected This is particularly important because often there is no apparent connection (in the mind of the patient) between these symptoms and the complaints which are paramount in his mind and which determined his consultation with the physician

General Symptoms. If the patient has not spontaneously mentioned the general repercussions of the disease, it is convenient to rapidly review the systems in order to discover possible general symptoms: *weight loss* or *gain* (either could be related to a cardiovascular disorder); *weakness* or *fatigue,* which can be a manifestation of circulatory disease, the result of poor circulation due to arteriosclerosis, the consequence of poor circulation in the brain, the hypophysis, or the adrenals, or the result of diminished cardiac reserve because of failure or poor oxygen saturation in the blood (cyanotic types of acquired or congenital heart disease). Finally, previous or present existence of *fever* should be investigated to the satisfaction of the clinician. Whatever the opinion of the patient in this respect, the clinician will check the temperature of the patient, especially if an elevation had been noted, because the disease may be associated with fever. For example, the study of temperature is indispensable in rheumatic heart disease. Fever can be a present sign or there may be a history of febrile episodes It is obvious that the patient can seldom see the connection between these episodes and the main form of heart disease. A careful study of the fever and its type and evolution is also indispensable in cases where bacterial endocarditis is suspected, and in cases of acute or chronic pericarditis. Its study is also indispensable in systemic diseases with cardiac or circulatory involvement, such as periarteritis nodosa, lupus erythematosus, etc.

Use of Medication. One more question in which either positive or negative data are useful is that referring to the use of *drugs.* Whenever a drug has been tried in the past, one has fewer doubts about its repeated use, or its results may have diagnostic importance For example, if the dyspnea of an emphysematous patient was *not* influenced by prolonged digitalization, doubts in regard to a possible relationship with heart failure are eliminated

A paresthesia of the left arm that extends to the neck, *sternum,* and precordium may leave doubts in the mind of a physician. If this complaint has completely and quickly disappeared after use of a nitroglycerin pill, this represents an element in favor of the coronary nature of the pain On the other hand, the negative result of the drug will also have an important negative value.

If the study of therapy is of aid to diagnosis, it is also often helpful from the point of view of treatment because sometimes it will permit

and an exact narrator. Then, the clinician has only to take notes and transcribe, as exactly as possible, the patient's statements. If, at any *moment, it becomes necessary to interrupt the* patient, the physician must be careful not to do it with an antagonistic spirit and must take the opportunity to make clarifying remarks without interrupting the thread of description. In this way, he can give the impression that he is following the answers with attention and interest. This will result in a vivid and dynamic transcription and an eloquent document which will open the way toward a correct diagnosis. In the words of Gallavardin, certain types of patients should be left free to talk. "Ceux qu'il faût laisser parler" The patient may be an introverted and withdrawn individual who tries to reduce and minimize the importance of his complaints This patient should be questioned at length, and the facts which have not been spontaneously given may have to be gathered through repeated and painstaking questioning Sometimes the patient even convinces himself of the nonexistence of undesirable disturbances. These patients are those which should be "forced to talk." In the words of Gallavardin, these are "Ceux qu'il faût faire parler." On the other hand, in these, as in any other patients, suggestive questions or questions with implicit answers should be *scrupulously avoided:* the important data can be obtained with questions which seem indifferent or neutral.

If the patient is, on the contrary, verbose and garrulous, and loses himself in empty descriptions or reports of unimportant opinions, then, without showing impatience, one should try to take him to a more solid ground and guide him with pertinent questions If these are not *sufficient to fulfill the objective*, sharp and direct questions should be used These patients are those whom one should try to keep quiet. (As Gallavardin says, "Ceux qu'il faût arrêter de parler.") In such cases, it is impossible to transcribe literally the patient's statements. With this type of patient, the report will be a kind of summary, with the exception of certain descriptive and exact expressions, which will have to be reported literally

Identification of the Symptoms. It is generally supposed that the chief symptoms of the present illness are included in the spontaneous description of the complaints. The clinician should proceed to identify these symptoms because frequently the doctor and the patient give different value and connotation to the same words. *Is the gasping for breath or suffocation* that the patient describes a real *dyspnea*, or is it a different phenomenon? Is the sensation of palpitation that the patient complains about real *palpitation;* is it only the impression of the normal beat of the heart felt by the patient when he puts his hand over the precordial region; or is it the sensation of the pulse of the carotid artery or of one of the arteries of the extremities? Is the swelling of the feet, described by the patient, a real *edema* of the lower extremities, or is it the sensation of fullness which is sometimes experienced in the lower extremities without edema?

Analysis of Symptoms. Once the identification of the symptoms has been accomplished and the clinician is certain that the same language has been used by doctor and patient, or that they have reached an agreement about the meaning of certain terms, the clinician will proceed to the *interpretation of the symptoms* which have been reported. He will start by selecting those of major importance. This is judged by the severity of a complaint, or because it has been the first in appearance or because, being that of greatest diagnostic value, it will serve as the center of the puzzle around which the other symptoms may be grouped To be considered are the magnitude and intensity of the complaints, their frequency, the causes of their appearance, the circumstance under which they were ameliorated, physical and psychological repercussions, symptomatic associations, evolution, and other pertinent information.

Integration of Syndromes. Thus, the keen clinician should proceed with ease from a significant symptom toward the *integration of a syndrome*, either by grouping the other necessary symptoms around the key symptom, or by obtaining them from the patient Therefore, if one of the elements needed to complete the syndrome is lacking and has not been supplied spontaneously, the clinician will ask a direct corresponding question, taking into consideration that the fundamental data have already been given by the patient

Suppose that a cardiac patient spontaneously complained of dyspnea, palpitation, arthralgia,

woman may supply facts of value: the number of pregnancies, their course and tolerance, their possible repercussion upon the cardiovascular system, it should be kept in mind that pregnancy represents a major test of cardiac reserve

Finally, two specific points should be investigated. Did the onset of the present clinical picture coincide with some *infection* or did the latter appear when heart disease already existed? Were there any foci of infection before or at the beginning of the disease? Were they treated surgically? This is especially important in regard to dental interventions which may appear innocuous in retrospect, although frequently causing *bacterial endocarditis*. This should be particularly investigated in patients who are predisposed to this disease because of organic valvular lesions Previous disease of the urinary passages and of the prostatic gland should also be ascertained In them, unfortunately, the antibiotics yield far less protection against bacterial dissemination due to surgical procedures than in interventions in the buccal cavity.

Nonpathological Personal History. The place of origin of the person and the place or places where he resided can have a special interest in certain types of heart disease such as the *myocarditis of Chagas' disease*, this requires the existence of a carrier, which is found only in certain geographic areas

The patient should be asked about his *habits*, his work, the amount of physical strain to which he is submitted, the environment in which work is done, emotional tension, and his likes or dislikes concerning his work. All this is important because the *emotional factors* are significant *in the* origin, maintenance, and development of circulatory disorders such as arterial hypertension, and for the influence which they may have in other circulatory disorders

The *physical strength* needed in the work of the patient, the type of life he has conducted, his practice of sports, should be noted because of the part they may have, more in the aggravation of a cardiovascular disorder than in its appearance

The patient is to be asked about his *dietary habits* and about his nutrition and weight, as obesity favors a more rapid evolution of several cardiovascular *diseases*, while malnutrition not only can aggravate any heart disease but can be the cause of certain cardiovascular disorders Soma Weiss (1931–1940) has revealed that beriberi may occur in Western countries and that it may be associated with important cardiovascular disorders

Smoking. The patient's habits of smoking (smoker or nonsmoker) should be recorded with care because, although it has not been proved that tobacco itself can be the cause of cardiovascular diseases, there is sufficient clinical evidence to confirm that in many cardiovascular patients it is definitely noxious This is particularly true in arterial diseases and especially in thromboangiitis obliterans, arteriosclerosis obliterans, coronary heart disease, cor pulmonale, and arterial hypertension.

Alcoholism. Alcoholism has an importance in the clinical picture of cardiovascular *patients* because it may be responsible for the appearance of *beriberi*, even in persons who receive adequate nourishment. It is interesting *also* because of its possible interference with good nutrition This is especially true in cases of dipsomania The hepatic damage caused by alcohol is also important in the clinical picture of the cardiovascular patient The degree of *inclination* for alcohol should be investigated, the type of beverage, the amount of intake, if it is a regular habit, if the patient is a social *drinker, or*, on the contrary, a true dipsomaniac.

Other Toxic Agents. Other toxic agents are *less* important because they are more rare but still should be investigated Among them, however, two should be kept in mind. (1) Drugs *like Benzedrine* may be taken in undue quantity in order to reduce the appetite. They may *cause* cardiovascular disturbances, tension, nervousness, and other symptoms (2) The excessive use of *barbiturates* and other sedatives may cause an increase of disturbances, *like* the dyspnea of Cheyne and Stokes It is not rare to learn that the patient is making use of a combination of drugs· a stimulant during the day and a sedative at *night*

Family History. The data concerning his family's medical history, which the patient supplies, are particularly important as far as rheumatic heart disease is concerned, because of the possible importance that hereditary factors have *in this* condition. It is true that the facts which serve as a basis for this theory are liable to be differently interpreted because all

the discovery of susceptibility, intolerance, or toxic manifestations of drugs. This knowledge will avoid errors in treatment and will save undue annoyance or danger. However, one can find many cases in which the patient cannot supply useful data.

Pathological History. The patient should be questioned about past diseases. If there is a negative answer in regard to the past, the physician will inquire directly with specific questions about the most important diseases. One of them is *rheumatic fever*, and one should inquire whether it has been present in its typical picture (including severe and migratory polyarthritis, fever, sweating, etc.) or whether it recurred in a less typical form. This is often called "growing pains," and consists of recurrent periods of fever during infancy or adolescence, often accompanied by epistaxis, and following attacks of tonsillitis. This clinical form is often followed by a long period of convalescence Erythema marginatum, nodules, and chorea may also be recognized through careful questioning.

A history of *syphilis* or of other venereal diseases gives an idea of the sexual behavior of the patient and the opportunity to suspect a form of syphilis which the patient did not identify or wished to keep hidden Clinicians know how difficult it is to identify with certainty in the history a syphilitic chancre many years after its disappearance, particularly because the patient may have forgotten it entirely. The result of serological tests at the moment of appearance of the chancre or right afterward may, on the contrary, be remembered and can be very useful. Again, a patient may remember that he was submitted to a specific treatment, and may remember its duration, the type of drugs used, and possibly the dose The collection of these facts could be very useful in the differential diagnosis of aortic valvular disease in an adult, whether or not there are precedents of rheumatic disease A very difficult diagnostic problem is gradually disappearing through the progressive diminution in syphilis, thanks to the effects of better medical education and the use of new and effective drugs.

It is necessary always to question a possible history of *diabetes*, even though this may be benign or controlled, because of the frequent vascular deterioration which accompanies this disease Its detection is especially important in the cases of cardiovascular diseases of arteriosclerotic nature in relatively young persons. The data of personal history will have to be integrated by the study of the family history, the examination of the fundus, and a glucose tolerance test.

Data dealing with a history of *arterial hypertension* should be carefully investigated. Besides clinical facts brought about by hypertension, which will be directly asked, it will be useful to ask if any degree of hypertension was found during any previous physical examination. In particular, it is pertinent to ask the patient if he ever was examined for life insurance, if he was accepted or rejected, or if he had to pay an extra premium. In the last two instances he should be asked if this was due to arterial hypertension. The confirmation by the patient that blood pressure had been normal may be followed by further questioning The date of the last examination may be such a long time before that hypertension may have developed since. On the contrary, it may have occurred recently, at a time when heart failure or myocardial infarction might have masked the hypertension The same line of questioning applies to physical examination by the Armed Forces.

The existence of *renal disease* should be investigated and also the signs and symptoms of systemic diseases, such as *fibroblastic diseases*, which so often have repercussions upon the heart and which could have originated a complex cardiovascular syndrome.

Other data which should be requested are those dealing with *diseases of the respiratory system* bronchial asthma, bronchitis, tuberculosis, pneumoconiosis, pulmonary infarct, pneumonia, and others All of them may be related to a possible *cor pulmonale*.

Then, pertinent questions should be asked in reference to *endocrine disorders* disturbances of the thyroid, hypophysis, adrenals, ovaries, and other glands, and questions pertaining to the possible appearance of diseases causing *anemia*

A fact which can only be revealed by questioning is the history of *trauma*. This might be the cause of an arteriovenous fistula which may be responsible for cardiovascular disorders A trauma, a violent effort, or an accident may initiate a *dissecting aneurysm*.

Questions dealing with the *marital life* of a

woman may supply facts of value: *the number of pregnancies*, their course and tolerance, their possible *repercussion* upon the cardiovascular system, it should be kept in mind that pregnancy represents a major test of cardiac reserve.

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members of a family, living in the same environment, are exposed to the same bacteria.

The vascular diseases, including coronary heart disease, may have a definite "family pattern"; even though a positive family history is not necessary to make a diagnosis, the existence of family data could be important in confusing and atypical cases.

In the juvenile type of arteriosclerotic vascular diseases, a family history of diabetes can be very important, even if there is no personal history of this disease. In these cases, a glucose tolerance test should be performed. It may reveal a latent or potential form of diabetes which, even though hidden, is active as a favoring cause of vascular deterioration.

The diseases of the fibroblastic system frequently have a definite family pattern The various patients do not have the same disease and there may be multiple forms in different members of the same family.

Myodystrophy and *neurodystrophy*, well-known familial and hereditary conditions, can produce myocardial dystrophy, and there are cases where the muscular dystrophy appears primarily or predominantly in the myocardium. Such cases may be encountered for example in *Friedreich's disease*, in *atrophic myotonia*, or in *Charcot-Marie-Tooth disease*

It is convenient on occasion to investigate carefully (especially when dealing with a patient who seems to have a severe cerebrovascular picture) whether the patient has been complaining of *migraine* and if he belongs to a family with a history of migraine Obviously, a patient with migraine can either simulate or present an organic cerebrovascular disease The history may reveal that, among members of the family with migraine, some have had occasional or recurring complaints similar to those of the patient.

The investigation, not always easy, of the pathology of *pregnancy* can be very important in detecting the cause of a congenital heart disease. Infectious (chiefly viral) diseases of the mother during pregnancy, obstetrical trauma, and others may be among them.

After completing the interrogation, the physician should be able to make a provisional diagnosis, not only in regard to the present disturbances, but also in regard to the underlying disease.

When dealing with a syndrome of congestive failure, the study of its evolution may show that the present clinical picture was preceded by a syndrome of variable duration and gradual severity of pulmonary congestion (evidence of left heart failure or mitral block) which practically disappeared after the onset of peripheral congestion (evidence of right heart failure). If this occurs in a relatively young person with a history of rheumatic fever, a presumptive diagnosis of mitral valvular disease can be made.

If the syndrome is chiefly that of left heart failure, if it has been preceded by the manifestations of arterial hypertension, if the patient has already presented visceral evidence of ischemia, if the circumstances and heredity are themselves suggestive, a presumptive diagnosis of hypertensive cardiovascular disease with heart failure should be made.

The dietary habits and alcoholic history can give an explanation of a syndrome of cardiac failure which appears without apparent reasons by suggesting a tentative diagnosis of beriberi heart disease.

Examples of presumptive diagnoses could be multiplied indefinitely. But it should not be overlooked that all this is only presumptive and may be confirmed or modified by physical examination and by the functional exploration made in the laboratory

3

General examination

PEDRO COSSIO

In the diagnosis of diseases of the cardiovascular system, the general examination may reveal the following symptoms: a particular *facies* and a special *habitus*, alterations in respiratory movements, pallor, cyanosis, jaundice, erythemata, petechiae, or nodules; edema; modification of local or general temperature, evidence of visceral congestion, pleural effusion, ascites, and certain alterations of the eye ground. Moreover, general examination should consider the body build, the body weight, and diuresis

FACIES

Modifications in the physiognomy, color, and even the conformation of the face may be produced by diseases of the heart; *some of these* modifications are so characteristic that a diagnosis can be made because of them. The fundamental types of facies which *one should* recognize are three. cyanotic, pallid, and dyspneic.

Cyanotic Facies. Various degrees of bluish coloration of the skin of the face *may occur* in cardiovascular diseases whenever there is a low oxygen concentration of the arterial blood due to arteriovenous shunt (congenital heart disease, pulmonary arteriovenous fistula), or alveolar hypoventilation (chronic cor *pulmonale*) Cyanosis is also produced by slower circulation of the peripheral capillary bed (heart failure, aortic aneurysm compressing the superior *vena* cava, rupture of the aorta into the vena cava or right heart) *Any one of these factors* may act alone or in combination with another.

The cyanotic color due to *low* oxygen *concentration* involves *the* whole face, including the conjunctivae, although it is generally more intense in areas with finer integument, such as the lips, the ears, and occasionally the cheeks.

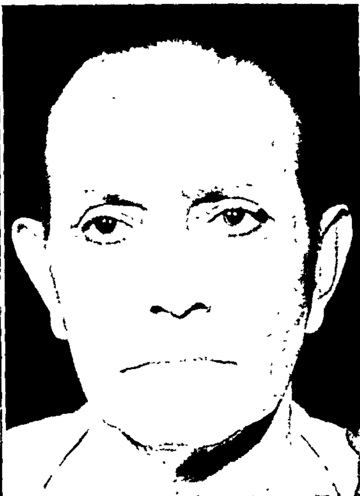
Cyanosis may be present *at birth* or start shortly thereafter; in this case it is usually due to *congenital heart disease with a primary arteriovenous shunt* (pulmonary stenosis with ventricular or atrial shunt, transposition of the large vessels, or tricuspid atresia plus shunts, Fig 3-1A).

If the cyanosis has its onset *during adolescence or early adulthood*, it is generally due to *congenital heart disease with a secondary arteriovenous shunt* caused by right heart failure or pulmonary hypertension (atrial or ventricular septal defect, persistence of the ductus arteriosus, or Eisenmenger's complex, usually associated with pulmonary arteriosclerosis).

If it should appear *later in life*, it is due to primary or secondary pulmonary hypertension with right ventricular hypertrophy (*chronic cor pulmonale*, especially if there is cardiac failure). In this last circumstance, the facies is so characteristic that it justifies the name of "*black cardiacs*" (Ayerza). In this condition *there is*, *in* addition to severe cyanosis, also a *puffiness* due to edema, caused more by deficient lymphatic drainage (increase in intrathoracic pressure) than by venous hypertension. This is so marked that, if the examiner is not experienced, he may confuse it with *the facies* of mediastinopericarditis, which is cyanotic and puffy.

The cyanotic facies caused by *venocapillary stasis* has different characteristics. The bluish color is *seen only* in the more prominent areas of the face, such as cheeks and chin; it never acquires such an intense hue and is always blu-





A B

Fig. 3-1. A. Cyanosis and clubbing of fingers (tetralogy of Fallot) B Pallor (aortic stenosis).

ish; it is typically found in mitral stenosis (*Corvisart facies*), except in extreme conditions where the whole face may be involved However, there never is such a deep blue color as in congenital heart disease or in compression of the superior vena cava, rupture of the aorta into the right heart, or advanced cardiac failure. In the latter condition, there is often added a yellowish or greenish tint due to hyperbilirubinemia resulting from chronic hepatic congestion. This is the so-called *olive-colored facies*, which is seen in combined mitral and tricuspid valvulitis In such cases, there always is a certain degree of low pulmonary oxygen saturation as a result of the so-called "mitral lung" (Cossio and Berconsky)

Pallid Facies. Different degrees of facial pallor, even in cardiovascular disease, may be due to the existence of *anemia*. A pale facies is often found in *active rheumatic carditis* or *bacterial endocarditis*, the former more frequently in children and adolescents, the latter, in adults.

It may also be due to arteriocapillary vasoconstriction, such as is found in advanced phases of arterial hypertension, particularly in the malignant stage (*pallid hypertension of Volhard*), in advanced stages of insufficiency and stenosis of the aortic valve (*aortic facies of Huchard*, Fig 3-1B), in a stage of extreme precordial pain (so-called angina pectoris), in peripheral vascular collapse, and in cases with cardiogenic shock, like that due to myocardial infarction with acute pulmonary edema In the latter instance, there is often added a slightly bluish tint, due to capillary stasis, which produces a characteristic grayish or lead-colored hue (*café-au-lait facies of Libman*)

Dyspneic Facies. The dyspnea produced by left heart failure or any other cause lends to the face such particular characteristics that the term "dyspneic facies" is amply justified It is characterized by a physiognomy of *anxiety* The eyes are bright and the look is apprehensive The facial features are pronounced, there is dilatation of the nares, there may be



Fig 3-2. A Orthopneic position (severe left heart failure) B. Position of Mohammedan prayer.

oral breathing The head may be erect and in slight dorsal flexion as it rests over pillows or the back of a chair, or it may be flexed anteriorly and supported by both hands The more acute and intense the dyspnea, the more accentuated are these characteristics Extreme dyspnea occurs in cardiac asthma, acute pulmonary edema, and acute cor pulmonale

POSITION

There are two types of position which have a diagnostic significance in cardiovascular diseases the erect or orthopneic position, and the fixed position

Orthopneic Position. This consists of an active, semisitting position in bed in patients with dyspnea due to stasis of the blood in the lungs as a result of left ventricular failure, mitral block, cardiac tamponade, or acute cor pulmonale (Fig 3-2A) When the stasis is of an extreme degree, the sitting position *is not* sufficient and the patient bends the trunk forward, either sitting in bed (and usually embracing a pillow, *pillow sign, position of Mohammedan prayer,* see Fig. 3-2B) or sitting on the edge of the bed with the legs hanging *or* resting on a chair Sometimes the patient will remain standing with the trunk leaning forward, the arms on the back of a chair or the head of the bed This has the objective of reducing venous return to the heart by the action of gravity and kinking of the large veins at the groin (Harrison)

If there is a concomitant *pleural effusion,* predominantly or exclusively in one hemithorax (as generally occurs in severe heart failure), the semisitting position is modified by bending toward the side of the effusion

Fixed Position. The patient keeps completely still, as if he were nailed to the floor. This position is adopted in cases with precordial pain following exertion or emotion Often the hand is placed over the precordial area or the midchest, with the fingers closed in the form of a claw (*main en griffe*) If this occurs while the patient is walking on the street, he hides his inability to continue walking by pretending to wait for a bus, or stopping to look through a show window (Vaquez)

In cases of paroxysmal precordial pain, the patient also adopts this position while hoping to control the pain with nitroglycerin. If the attack occurs while in bed (*angina decubitus*), the patient assumes a sitting or standing posi-

tion. On the other hand, if the pain is prolonged and severe, the patient moves about and cries for help.

CONSTITUTION

The somatic and emotional constitution should be established in all cardiovascular examinations, not only because of the predisposition which may occur in certain diseases but also, and principally, because of the anatomic and physiological characteristics of the heart in extreme constitutional types

Agitated, apprehensive, and *executive temperaments* and certain *anxiety states* predispose the individual to arterial hypertension and early arteriosclerosis.

A *longilinear* somatic constitution presents a *vertical heart* with a small transverse diameter and generally with a clockwise rotation over its longitudinal axis, an elongated vascular pedicle, and an aortic arch which is placed in a more anteroposterior axis.

On the other hand, the *brevilinear* somatic type has a *horizontal heart* with a wider transverse diameter and usually a counterclockwise rotation over its longitudinal axis The vascular pedicle is wider and the aortic arch has an axis which is in an oblique direction toward the left.

RESPIRATORY MOVEMENTS

The respiratory movements are more frequent than normal (*polypnea*), possibly surpassing 35 per minute (*tachypnea*) any time that there is congestion in the pulmonary circulation as a result of heart failure, mitral block, acute cor pulmonale, or cardiac tamponade. If there is a *deficient blood supply to the respiratory center* due to decreased cardiac output or cerebrovascular sclerosis, such as occurs at times in marked heart failure after the age of 50, the respiratory movements may alternately increase and decrease in frequency until brief periods of apnea appear (*periodic Cheyne-Stokes respiration*) This phenomenon is more noticeable, or may occur only, at night when the patient is trying to sleep, therefore, the physician may not have the opportunity to observe it and it will pass unnoticed unless he questions the persons who watch the patient They will invariably refer to the respiratory changes and, on many occasions, will add: "periodically the patient stops breathing and becomes so quiet that he appears dead while I lose my control because I fear that he will stop breathing forever." This is why the syndrome has been called *alternate agitation* (Cossio et al.).

Another modification of the respiratory movements is the so-called *sighing respiration,* a sign which is typical of anxiety syndromes While the patient is discussing his troubles, he will invariably mention a sensation of lack of air due to exertion or caused by being in a closed place or by a strong emotion, during which he does not feel better until he takes one or more deep breaths from time to time followed by forceful and noisy expirations

DIFFUSE PALLOR

A paleness of the skin of the trunk and extremities is the result of the same conditions which cause pallor of the face and is seen in the same circumstances: anemia (bacterial endocarditis, rheumatic carditis), deficient blood supply due to arteriocapillary sclerosis (generalized atherosclerosis with or without *arterial hypertension*), *or arteriocapillary vaso*constriction (aortic insufficiency, malignant hypertension, cardiogenic shock, or peripheral vascular collapse)

In the last instance, in addition to the cold and clammy skin, there may also be a *slightly* bluish tint due to the stasis of the blood in the capillary bed, which, combined with pallor, produces a typical grayish or lead-colored complexion

In the correct interpretation of pallor of the skin in diseases of the heart, it is well to remember that the former does not invariably depend on the latter since pallor may be due to hypothyroidism with myxedema, to arterial hypertension with renal sclerosis, or to anemia caused by chronic uremia There may also be anemia which is not the cause of heart disease (chronic anemias, particularly the hemolytic type, or a sickle-cell anemia) Superimposed on the pallor, there are often variable degrees of yellowish coloration (due to hyperbilirubinemia in hemolytic anemias, and to other causes in myxedema and uremia).

A paleness of the skin is not always diffuse but may involve only certain regions, such as the distal part of one or two extremities or

perhaps merely one or two fingers In this case, it is always accompanied by coldness of the skin and is due to a lack of blood supply as a result of vasospasm (*Raynaud's syndrome*), thrombosis (atherosclerosis, thromboangiitis), or the effect of embolism originating in the left heart (mitral stenosis, myocardial infarction, bacterial endocarditis, atrial fibrillation). Such an embolus may also arise in the right heart or venous system (*paradoxical embolism*) passing through an abnormal shunt between the right and left hearts (atrial or ventricular septal defect).

CYANOSIS

A bluish tinge of the skin of the trunk and extremities resulting from cardiovascular disease is produced by an *increase in reduced hemoglobin content of the capillary blood.* To be clinically visible (*cyanotic threshold*), this should reach at least a content of 5 per cent It can be due to low oxygen saturation of the arterial blood (*central cyanosis*) as a result of either a venoarterial shunt (congenital heart disease, pulmonary fistula) or reduced alveolar intake of oxygen (cor pulmonale) On the other hand, it may be the result of greater reduction of oxyhemoglobin in the capillaries due to slow circulation (*peripheral cyanosis*) determined by heart failure or venous or arterial obstruction (following pallor, in the last instance) of either organic (extrinsic pressure, thrombosis, embolism) or vasomotor origin (Raynaud's syndrome, acrocyanosis)

Central cyanosis is of a *diffuse* type and includes the mucous membranes, particularly those of the mouth below the tongue, although occasionally it is more intense in distal points An exception is represented by the *persistence of the ductus arteriosus with reversed flow* on account of pulmonary hypertension; in this case, the head and upper extremities have a normal color, in contrast to the bluish tinge of the lower extremities due to the mixture of venous with arterial blood, distally to the origin of the carotid and subclavian arteries.

In contrast, peripheral cyanosis is of a frankly *distal* predominance, and is particularly noticeable in the hands, feet, and other distal appendages, if the stasis is diffuse, as in heart failure It may be localized to a certain segment of the body if the stasis is due to venous or arterial occlusion. In either case the temperature of the skin is decreased, in contrast with the normal temperature in central cyanosis

In general, in the final stages of cardiac diseases, cyanosis develops into a mixed type, be it primarily central (congenital heart disease or cor pulmonale with failure) or primarily peripheral (heart failure with "cardiac lung," particularly in cases of rheumatic valvulitis with mitral lesions). In such conditions, the cyanosis is diffuse, although it predominates in distal points; it may acquire such an intensity that the bluish coloration becomes almost black, justifying the term *black cardiac* suggested by Ayerza for the stage of chronic cor pulmonale with failure.

The exact appreciation of the peripheral or central nature of the cyanosis of the skin and mucous membranes, as well as the relative proportions of one or the other type in the case of a mixed cyanosis, may be realized by determining the oxyhemoglobin content of arterial, venous, and capillary blood, that of the latter is deduced by subtracting the oxygen content of the two previous after determining the oxygen capacity of the blood and remembering that 1 34 ml of oxygen are fixed by 1 Gm of hemoglobin

Normally, the blood fixes 20 volumes of oxygen (saturation capacity) which is equivalent to 15 Gm of hemoglobin Also, the arterial blood normally contains 19 volumes of oxygen and the venous blood 14 volumes of oxygen (arteriovenous difference of 5 volumes of oxygen). Thus, arterial blood contains 14.25 Gm of oxyhemoglobin (95 per cent saturation) and 0 75 Gm of reduced hemoglobin (5 per cent desaturation) while venous blood contains 10 50 Gm of oxyhemoglobin (70 per cent saturation) and 4 5 Gm of reduced hemoglobin (30 per cent desaturation). That is, capillary blood contains $(A + V)/2$, or 12 37 Gm of oxyhemoglobin and 2.12 Gm of reduced hemoglobin

In the case of *central cyanosis*, the desaturation of arterial blood is increased and the arteriovenous difference is normal In the case of *peripheral cyanosis*, the arterial desaturation is normal and the arteriovenous difference is increased to such a degree that the desaturation of capillary blood is as high as 7 volumes of oxygen, which is equivalent to about 5 Gm of reduced hemoglobin, the minimum necessary for the integument to take on a cyanotic

tint (*cyanotic threshold*). In *mixed cyanosis*, there is greater arterial desaturation and greater arteriovenous difference, to such a degree that the capillary blood contains more than 5 Gm of reduced hemoglobin and exceeds the cyanotic threshold.

It should be remembered that the cyanotic threshold is modified by other factors. Apart from the density and capacity of the capillary bed, due to genetic, vasomotor, and organic factors, and the quantity of hemoglobin (anemia?) there is the factor of the *melanin* content of the skin which may mask the coloration produced by blood in the capillary bed. *Obviously, a larger quantity of reduced hemoglobin* is necessary in the capillary bed in order to produce cyanosis in Negroes than in Caucasians and vice versa. A lack of cyanotic coloration of the skin due to these factors, even though there may be more than 5 Gm of reduced hemoglobin in the capillary blood, may be termed *occult cyanosis*.

JAUNDICE

A yellowish or even greenish coloration of the integument, due to hyperbilirubinemia above 2 mg per 100 Gm (*icteric threshold*) as a result of cardiovascular disease may present itself in two conditions: in *pulmonary infarct* due to embolism with acute cor pulmonale, and in the final stages of *right heart failure* of long standing, such as in rheumatic valvulitis with tricuspid lesions.

In pulmonary infarct with cor pulmonale, the yellow color of the integument is generally very light, often only seen in the conjunctivae (*subicterus*). There is no bilirubinuria; the hyperbilirubinemia is due to the hemolysis and reabsorption which takes place in the infarcted zone, and the liver is not capable of eliminating it through the biliary tract because there is hepatic embarrassment due to the circulatory condition (drop in cardiac output, venous hypertension, anoxic anoxia). The evolution of the jaundice in this case is regulated by the cardiopulmonary process and, therefore, has no prognostic significance, contrary to that of other conditions.

In the later stages of chronic heart failure of long standing, particularly right heart failure, the yellowish coloration of the skin may be light, lemon-colored (flavinic), or it may be more intense and have a greenish or olive color (verdinic). Furthermore, there is generally bilirubinuria, due to a mixed mechanism caused by alterations of the hepatic parenchyma secondary to congestion and hypoxia (detrabeculization, centrolobular necrosis). Naturally, this type of jaundice has a more grave prognostic significance than the purely cardiac type, but an independent form of hepatitis should be excluded.

ERYTHEMATA, PETECHIAE, AND NODULES

Circumscribed, reddened areas of the skin *due to hyperemia and blanching with pressure* (*erythemata*) may have a direct or indirect relation to certain cardiac diseases.

Erythema marginatum, constituted of flat rose-colored spots, arranged in circles interlacing one another and producing virtual arabesques, is found mostly over the trunk and extremities, although possibly also on the face, hands, and feet. It is found with relative frequency in serious cases of *rheumatic fever* with carditis, more frequently in children and adolescents than in adults, and more in the Northern Hemisphere than in the Southern. Also in rheumatic fever, there may appear rose- or salmon-colored spots which are raised and, therefore, constitute true *nodules*, hence, the term *erythema nodosum*. It is found mostly on the legs and near the joints, more frequently in children or adolescents. At times, the erythema of rheumatic fever does not have definite or uniform characteristics. The rose-colored spots have form, size, and distribution of a most varied type and, therefore, receive the name of *polymorphous*.

Petechiae are reddened and circumscribed areas of the skin. They are due to small hemorrhages and therefore do not disappear with pressure, this can be appreciated by pressing the skin with a small glass slide and observing them through it. Petechiae are found in cases of *acute bacterial endocarditis* and in the advanced stages of the *subacute* form. They have a marked red color at the moment of their appearance and disappear in 3 to 5 days after passing through purple, greenish, and yellow stages, due to transformation of the extravasated blood pigment. They are usually found on the chest, abdomen, supraclavicular fossae,

palate, conjunctivae, and retina; they are usually round and vary from the size of a pinhead to that of a pea, except for the subungual variety which has a linear aspect

Hemorrhagic, lenticular, erythematous *maculae*, sometimes papular, always nontender, are found on the soles of the feet and palms of the hands and usuaally appear in *bacterial endocarditis*, mostly in the acute type (*Janeway lesions*).

Dermic, subcutaneous, and even subperiosteal *nodular formations*, usually very small, from ½ to 5 mm in diameter, and exceptionally larger, may be found in certain cardiac diseases, such as active rheumatic fever, subacute bacterial endocarditis, and atypical verrucose endocarditis (*Libman-Sacks disease*).

Nodules of rheumatic origin, known as *Meynet's nodules*, are about the size of a grain of rice, although at times they may be much larger. They are found in the subcutaneous tissue, always adherent to the underlying layers, such as aponeurosis or periosteum, and are usually located on the extensor aspects of the joints (wrist, elbow, knee, and ankle) At the moment of their appearance, they acquire their maximum size, are of somewhat soft consistency, and may disappear in a few days Should they become hardened, they would persist indefinitely. They are found chiefly in *chronic, active rheumatic fever* with progressive rheumatic carditis, more commonly in the Northern Hemisphere than in the Southern.

The *nodules* of subacute bacterial endocarditis, known as *Osler's nodes*, are usually found at the tips of the fingers, on the palms, and on the soles of the feet. They begin as acutely tender areas turning, several hours later, into rose-colored miliary maculae (having the size of a grain of millet or less) They are usually *recognized* only by blanching the area with *pressure from* a glass slide They disappear after 2 or 3 days, only to reappear in other areas.

Flattened nodules with a central depression, confluent or *independent*, found in erythematous zones, usually on the bridge of the nose and on the cheeks, with the classical *butterfly configuration*, constitute the *cutaneous manifestation* of the systemic disease known as *disseminated lupus erythematosus*. This often presents visceral manifestations with cardiac or pericardial involvement and the atypical type of verrucose endocarditis described by Libman and Sacks.

EDEMA

The interstitial infiltration of water into the subcutaneous tissue (*subcutaneous edema*) is an important sign of heart disease It occurs in right heart failure and complete advanced failure regardless of its cause, and in cases with mechanical or dynamic difficulty of cardiac filling (constrictive pericarditis, tricuspid stenosis, thrombosis, tumors, or extrinsic compression of the right atrium or ventricle). It is due primarily to *venous hypertension*, which usually accompanies these conditions, *together with* capillary hypertension. The increase of the hydrostatic capillary pressure is followed by greater passage of water and electrolytes *from* the intravascular to the interstitial and even intercellular compartments *Edema is* also due to retention of the sodium ion as a result of *deficient renal excretion* and, in some cases, to *defective lymphatic drainage*, caused by increase of intrathoracic pressure It is probably *connected* to endocrine factors such as the failure of the liver to destroy the antidiuretic and adrenocortical hormones as a result of deficient blood supply.

The fundamental clinical characteristic of edema is its location, which is conditioned by the force of gravity, so that it accumulates in the lower parts of the body (*dependent edema*). The skin is usually cold and cyanotic, except when there is anemia or vasoconstriction Therefore, in ambulatory individuals or patients who remain sitting with their feet hanging, the edema begins in the distal extremity of the lower limbs (*malleolar edema*). In the beginning, this occurs only at the end of the day and the edema disappears with the nocturnal decubitus (*evening edema*). Later, the edema is present even on the following morning (*permanent edema*), and little by little extends to the rest of the lower limbs, the external genitalia, and even to the trunk, seldom reaching above the level of the umbilicus, except in rare cases.

On the contrary, in patients confined to bed, the edema begins in the sacral region, extending first to the posterior aspect of the thighs, then to the rest of the lower extremities and

lumbar region, and finally to the external genitalia and anterior aspect of the abdomen (*sacral edema*) Even though this general scheme is often observed, the distribution may present certain variations according to the predominance of hydrostatic, renal, or lymphatic factors in its production.

The *hydrostatic factor* predominates in the production of edema in chronic heart failure due to valvular lesions, particularly mitral and tricuspid The swelling, in addition to being *cold and cyanotic* (the cyanosis is due not only to capillary stasis but also to a disturbance in oxygen intake—"Mitrallunge"), is usually in the lower half of the body, contrasting sharply with the thinness of the upper half resulting from the poor nutrition caused by alimentary restrictions and hepatic insufficiency

The *renal factor* seems to predominate in chronic heart failure due to arterial hypertension, generally with coronary heart disease, and in aortic valvular lesions The swelling, in addition to being *cold and pale* (vasoconstriction or anemia), is more diffuse, although always predominating in the dependent areas

When the *lymphatic factor* is predominant (as in heart failure of subacute, recurrent, or chronic cor pulmonale), the swelling is *intensely cyanotic, may or may not be cold*, and is generalized from head to feet, to such a degree that the facies may be similar to that of the superior caval syndrome

The clinical recognition of the cardiac origin of edema is usually simple It is sufficient to keep in mind the above-mentioned characteristics and the existence of cardiac conditions which may give rise to it Nevertheless, it sometimes happens that there is an organic heart disease capable of producing edema, and yet the existing edema is due to a renal disease, hypoproteinemia, or phlebothrombosis The differentiation is established by the fact that only in the first can one find the presence of systemic venous hypertension revealed by engorgement of the jugular veins and swelling of the liver, and by manometric determination

TEMPERATURE

Increase (*fever*) or decrease (*hypothermia*) of the body temperature may have some relation to disease of the heart. A *prolonged and irregular fever*, central as well as superficial, is a constant manifestation of bacterial endocarditis, occasionally of *rheumatic carditis* or *atypical verrucose endocarditis*. Fever of similar characteristics and of the same origin, but less prolonged, is found in *pericarditis* of various causation. Moderate fever of only a few days' duration, but only central and not superficial, is relatively frequent in *myocardial infarction*, due to destruction of tissues and subsequent reabsorption of proteic material.

An *oral or rectal central fever*, accompanied by normal inguinal or axillary (superficial) temperature due to diminution of the cutaneous radiation of animal heat, produced by cutaneous vasoconstriction consequent to the drop of cardiac output, is caused by cardiogenic shock, pronounced cardiac failure, or attacks of paroxysmal tachycardia.

VISCERAL CONGESTION

The passive increase (*stasis*) of blood contained in certain viscera (lung, liver, kidney, and even spleen) may be due to diseases of the heart

Pulmonary Congestion (cardiac lung). This is the most frequently observed type and depends on *venous pulmonary hypertension* due to left ventricular failure, mitral block (mitral stenosis), mitral regurgitation, fibroelastosis, obstruction of the left atrium by a myxoma or thrombus, or left-sided constrictive pericarditis. Pulmonary congestion of cardiac origin (the cardiac lung) is also produced by an unusually large quantity of blood circulating in that organ as a result of left-to-right shunt, as in large interatrial or interventricular septal defects, and in patency of the ductus arteriosus.

The principal clinical manifestation is *dyspnea*, due to the diminution of the vital capacity, at times accompanied by *cough* (either isolated or spasmodic, productive or nonproductive) and even by *aphonia* All of this depends on the stimuli applied to the endings of the vagus nerve by pulmonary engorgement, alveolar transudation, or compression of the left recurrent laryngeal nerve consequent to dilatation of the pulmonary artery

In chronic pulmonary congestion, the dyspnea also occurs *after severe exertion*, then *after moderate exertion*, and finally *at complete rest* In such cases, the patient must remain sitting day and night (*orthopnea*). On the other hand,

in acute pulmonary congestion *the dyspnea is paroxysmal*, occurring usually at night and occasionally with prolonged and noisy expirations due to bronchospasm (*cardiac asthma*) with or without spasmodic cough, aphonia, and abundant serosanguinous expectoration, or noisy tracheal rales (*acute pulmonary edema*).

An important clinical manifestation is *pulmonary hyperemia*, at first only found on radiological examination through extensive and marked hilar shadows, with or without mottling of the rest of the pulmonary fields This usually occurs first in the lower lobes and then involves the others. Later, when there is transudation into the alveoli, coarse, medium, and fine rales appear over the lung bases, progressing upwards until they reach the apices.

Hepatic Congestion. This condition follows in frequency and importance (*cardiac liver*), and is *due to systemic* venous hypertension caused by right heart failure, tricuspid stenosis, pericardial effusion, thrombi or tumors of the right atrium, or right-sided constrictive pericarditis. Initially, only centrolobular hyperemia appears, followed by *fatty degeneration* and centrolobular detrabeculization (*nutmeg liver*). Later, centrolobular necrosis appears and finally sclerosis, or fibrosis (*cardiac cirrhosis*). Usually, this is more pronounced in the left lobe of the liver than in the right, probably as a consequence of the less adequate drainage of the former due to the angle of its venous collector in relation to the inferior vena cava

The principal symptom is hepatomegaly, the liver is tender and varies in size according to the degree of cardiac insufficiency, but a constantly enlarged and nontender liver is found in patients with chronic congestion plus a variable degree of fibrosis (*cardiac cirrhosis*).

In the initial stage of hepatic congestion, the hepatomegaly may be absent, or at least *it may not* be clinically recognizable, and the only evidence will be a postprandial feeling of fullness or some degree of pain at the epigastrium or right hypochondrium This can occur after exertion and there may be tenderness upon palpation of the epigastrium

Renal Congestion. This occurs in the same conditions which cause a cardiac liver It is revealed by *oliguria without a proportional increase in specific gravity of the urine.* There is slight albuminuria, and there are red cells and casts in the sediment. In advanced cases, there is an increase in nonprotein-nitrogen content, particularly if there was a decreased renal reserve, such as occurs in heart failure due to hypertensive heart disease with or without coronary sclerosis.

Splenic Congestion. This condition is also caused by the elements which are followed by cardiac liver and renal congestion. It is often present when they are, but it may be sufficiently severe to be recognized by palpation in cases of chronic, severe heart failure in infancy or adolescence. This is generally due to rheumatic valvulitis and, therefore, may lead to confusion with bacterial endocarditis, especially if there is fever and increased sedimentation rate

The lack of splenomegaly in chronic right heart failure in the adult may be attributed to the replacement of the muscular and elastic tissues of the spleen by fibrous tissue (a common phenomenon of involution).

SEROUS EFFUSIONS

The accumulation of fluid in the serous cavities is found principally in the pleurae (*pleural effusion*) and the peritoneum (*ascites*) as a result of cardiac failure The pleural effusion may be a transudate (*hydrothorax*) or an exudate (*pleurisy of the cardiac*).

Hydrothorax is found in advanced stages of right heart failure, chiefly on the right side, although it may be bilateral or exclusively on the left. The effusion may be chronic, reabsorbed, or recurrent, in relation to the degree of cardiac insufficiency. *Cardiac pleurisy* is usually unilateral, either right or left. It is at times hemorrhagic, and is usually recurrent, in spite of improvement of the cardiac failure This is because it may be influenced also by the *subpleural pulmonary infarcts*, which are caused either by *pulmonary emboli* or by *phlebothrombosis of the pulmonary veins*, favored by *stasis* in the lesser circulation.

Ascites is always a transudate except in the case of repeated paracentesis, and in patients with a *syndrome of Concato* (tubercular polyserositis). It may be more of an exudate than a transudate in *Pick's syndrome* (perihepatitis with "iced liver" plus constrictive pericarditis). It may be found in long-standing right heart failure and is accompanied, therefore, by dif-

ferent degrees of cardiac cirrhosis in cases of rheumatic valvulitis with tricuspid stenosis and regurgitation.

OPHTHALMOSCOPY

The examination of the eye grounds, facilitated nowadays by fine instruments and direct illumination, is fundamental and even obligatory in a cardiac clinic, especially if one suspects arterial hypertension.

The alterations in the retina due to diseases of the cardiovascular system may be divided into two groups One consists of *general alterations* which follow systemic vascular conditions such as arteriosclerosis and arterial hypertension. The other group includes *focal alterations* due to local vascular conditions, such as an occlusion of one or more vessels of the retina due to thrombosis or embolism.

The general alterations are more or less diffuse and are always bilateral, although they may predominate in one eye The focal alterations, on the contrary, are unilateral or bilateral but always zonal

Arteriosclerosis of the retina is observed in arterial hypertension, diabetes, or senility It is characterized by arteries which are more tortuous than usual, an accentuated silver-wire reflex, and varying degrees of compression of the vein at the crossing of the arteries (*Gunn's sign*). In more advanced stages, there appear ovoid or linear white spots of *retinal atrophy*, fine, silver-wire arteries, *hemorrhagic, rounded or pointed spots* of different sizes which may be single or multiple and irregularly distributed. The most significant generalized alteration, because of its prognostic value, is *hypertensive retinopathy*, which, in its advanced stages, is always found in combination with different degrees of retinal arteriosclerosis. Initially the arteries of the retina present a diminished caliber with little or no whitish reflex and above all with a more or less rectilinear trajectory (silver-wire arteries), branching at more or less acute angles and with little or no compression of the veins over which they cross. In the case of *necrotic arteriolitis*, such as occurs in malignant hypertension and in the hypertensive vascular disease of pregnancy, the retina also presents linear or multiple-pointed hemorrhages whose major axis is directed toward the disk, conglomerated exudates which look like cotton balls, whitish fissures converging on the macula like spokes of a wheel (*macular star*), and, above all, different degrees of papilledema and even retinal edema, which starts at the posterior pole and advances toward the equator of the eyeball

Among the focal alterations, the most important is that caused by embolism of the retinal artery, frequent in mitral stenosis, less frequent in myocardial infarct, and rarely occurring as a result of paradoxical embolism. The retina is then intensely pallid with empty arteries and veins, which are, therefore, very difficult to recognize The multiple small embolisms of bacterial endocarditis are small hemorrhagic perivascular spots in which a whitish spot may be seen in the center.

Finally, of less interest to cardiology is *thrombosis of the central vein of the retina or one of its branches*, due to compression of these vessels by an arteriosclerotic process of the retina. In the case of the central vein, all of the veins are engorged, there are multiple hemorrhages, more numerous as they converge toward the disk, and, in the case of one of the branches, only the corresponding vein is engorged and there is a single neighboring hemorrhagic spot

4

Study of the pulse

Clinical Study of Pulse
Graphic Study of Pulse

ALDO A. LUISADA AND EUGENIO JONA

CLINICAL STUDY OF PULSE

Even though the examination of the pulse has lost much of the importance it had in the past, it may still yield much valuable information in the hands of an experienced physician

The study of the arterial pulse has had a large part in the physical examination of a patient since ancient times *Chinese physicians* described in detail *this study before 2500 B C* They examined the pulse of several arteries with light, medium, and strong compression of the vessel and reckoned the ratio between pulse and respiration. They also made a careful study of arrhythmias and discounted the importance of occasional "skipped beats" Good observations concerning the pulse can be found in the *Ebers Papyrus*, also dating to about 2500 B C Hippocrates gave details about the rate, amplitude, strength, and rhythm of the pulse, as well as about the rapidity of its rise (*pulsus celer* versus *pulsus tardus*) Galen added to these elements the tension and filling of the artery Weitbrecht (1734) observed that the carotid pulse preceded the radial His observation was purely clinical and was confirmed by graphic methods only one century later (Weber)

The following data should be noted in the examination of the pulse:

1 Is the pulse *regular* (*rhythmic*) or *irregular* (*arrhythmic*)? If irregular, the possibility that the irregularity occurs either *occasionally* or *periodically* (allorhythmic pulse) *should be* investigated by prolonged observation. If *the* irregularity occurs periodically, *then a possible* connection with the phases of respiration *should be investigated* (*respiratory arrhythmia* due to sinus arrhythmia). This is easily done by asking the patient first to breathe deeply and slowly (increase of the irregularity), and then to "hold his breath" (disappearance of the irregularity). The occasionally irregular pulse is called *intermittent pulse* One of the most common types of allorhythmic pulse is the *bigeminal pulse*· a small pulse, due to a premature beat, closely follows the main pulse wave Among the various types of irregular pulses, the following are common:

a Complete ventricular arrhythmia caused by *atrial fibrillation* There is a complete and nonperiodic irregularity. Frequently, there also is a *pulse deficit* i.e., a certain number of cardiac contractions not *revealed by the pulse* (one hand of the observer should be placed over the cardiac apex, the other over the radial artery)
b Multiple premature contractions. Frequent irregularities are followed by compensatory pauses.
c Periodic AV block The pulse is missing when there is no apex beat

2 Is the pulse *rapid* or *slow*? The rate of *the pulse* (number of pulsations per minute) should be noted. A very slow pulse rate (less than 80 in an infant, less than 60 in a child, *less than 40 in an adult*) *suggests heart block*

3 Is the pulse *celer* or *tardus*? *Pulsus celer* is that which quickly dilates the artery (typical of aortic insufficiency) while *pulsus tardus* is that which dilates the artery slowly (typical of aortic stenosis)

4. Is the pulse *small* or *large, soft* or *hard?* The first quality deals with *the volume of the pulse,* the second with the ease or difficulty of compressing the artery up to the point of disappearance of the pulse, namely, with the *pulse pressure.* A small pulse may be found in low blood pressure, mitral or aortic stenosis, heart failure, myocardial infarction. A large pulse can be found in hypertension, and may also be found in the tetralogy of Fallot. A condition of *rigidity* of the arterial wall may be noted as evidence of arteriosclerosis. Certain cases of malignant hypertension have a small, hard pulse (*metal-wire pulse*).

5. Is it *a pulsus alternans?* This type of pulse is perfectly regular but shows the alternate occurrence of larger and smaller pulse waves. It is due to a serious disturbance of left ventricular dynamics.

6. Is it *a dicrotic pulse,* having a second small wave after the peak of the main wave? This is found in fever, anemia, and bradycardia. In some cases, the pulse has such a high dicrotic wave that it may be confused with a bigeminal or alternating pulse.

7. How do *the two radial pulses* compare? This may reveal a smaller pulse on the left side (some cases of ductus arteriosus, aneurysm of the aortic arch, atherosclerosis of the aorta with narrowing of the left subclavian artery). In the case of aneurysm, the left pulse often is small and delayed. More exceptionally, a small pulse *on the right side* may be caused by aortic aneurysm, complex congenital lesions, or atherosclerosis of the aorta.

8. *Comparison of the radial with the femoral pulse* may reveal a small femoral pulse (coarctation of the aorta, embolism or thrombosis of the abdominal aorta). On the contrary, a large and strong femoral pulse with a small radial pulse is typical of aortitis with narrowing of both subclavian openings ("reverse coarctation"). A delay in the femoral pulse may be caused by aneurysm of the abdominal aorta.

9. A *thrill,* either over the forearm or over the femoral artery, may be found in aortic regurgitation, patent ductus arteriosus, aortitis, fever, hyperthyroidism, or arteriovenous fistula.

10. *Palpation of the temporal arteries* and of *the arteria dorsalis pedis* on both sides completes *the general examination and may reveal* local changes of pulsation (temporal arteritis; coarctation of the aorta, saddle embolus of the aorta).

11. In vascular diseases of the lower extremities, palpation of the popliteal, femoral, and posterior tibial arteries, as well as the dorsalis pedis artery, may give additional valuable information, particularly in cases of arteriosclerosis obliterans and Buerger's disease.

GRAPHIC STUDY OF PULSE

TRACINGS OF THE AORTA (AORTOGRAMS)

Aortograms of the horse were recorded by Chauveau and Marey (1863) and of dogs shortly afterward by Fick and Frédéricq. Frank used an optical system for recording aortograms of animals and his studies were followed by a score of others. The first human tracings were recorded by Mueller and Weiss. Clinical cases of aortitis or aortic aneurysm were studied later by graphic methods (Cardarelli, Zagari). Luisada (1953) made systematic studies of normal subjects and cardiac patients.

Technique. The aortogram may be easily recorded over three points: *the second right interspace,* the *suprasternal notch,* and the upper part of the *abdomen.* While the first record is influenced by waves due to direct cardiac motion, the second has less interference from cardiac waves. Whenever the aortic arch is dilated or blood pressure is increased, excellent tracings are obtained in this area and a pure arterial record can be observed. The abdominal aortogram is recorded slightly above the umbilicus, poor results are obtained when the abdomen is distended or obese, but a good tracing is obtained from lean individuals.

In all three types of aortogram, a funnel, connected to a "linear" microphone, is placed against the skin over the vessel. In the case of the suprasternal notch, the funnel is held by hand, or a suction cup is used. In the other two instances, a rubber band holds the funnel. The simplest way is to use a microphone as a support for the cup. Thus, simultaneous tracings of the aortic sounds and of the aortic pulse are recorded.

The linear microphone transforms pulsations of air into equivalent electrical pulsations, so

that the tracing can be recorded by a galvanometer of an electrocardiograph either on photographic film or by direct writing

Analysis of the Waves. The aortogram is essentially a tracing of the central pulse. However, tracings recorded on normal subjects at the second right interspace or at the suprasternal notch present additional waves; these are either due to changes of cardiac volume or are simultaneous with the heart sounds (Fig. 3-3). It should be kept in mind that considerable variations may occur in the tracing For this reason, the following description cannot apply to all tracings.

An *atrial wave in presystole* (*wave* 4), a small wave during the tension period, *wave* 1a); and a wave of rapid filling in early diastole (*wave* 3), are frequently observed The tracing shows *a steep rise* during ejection and may present a small depression in the ascending limb of the pulse (anacrotism). This is followed by a slower rise, a rounded peak, and a slow decline. The end of ventricular contraction and the onset of ventricular relaxation are marked by a sudden drop in the tracing (incisura). After this, one or more coarse vibrations may take place, then a drop in the tracing can be seen (*point* 0) followed by a high positive wave (*wave* 3) in *diastole*

As soon as the ascending aorta and the aortic arch are dilated by the pulse, the blood moves rapidly into the abdominal aorta and reaches the arteries of the legs The movement of blood during systole is complicated by the low

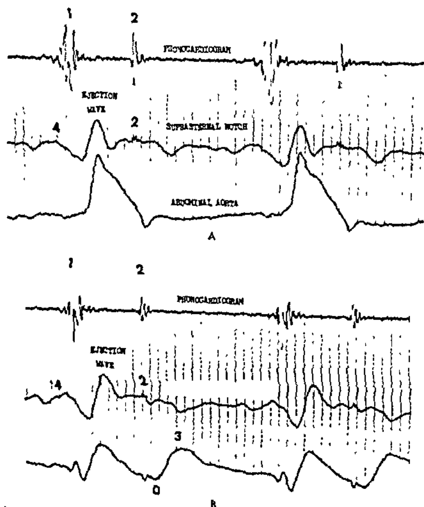


Fig 3-3 A. *Normal* subject. *Aortograms recorded at the suprasternal notch and the abdomen. Simultaneous phonocardiogram for timing.* B. Normal *subject Aortograms* recorded at the 2d right interspace (below) and suprasternal notch (above). *Phonocardiogram for timing.*

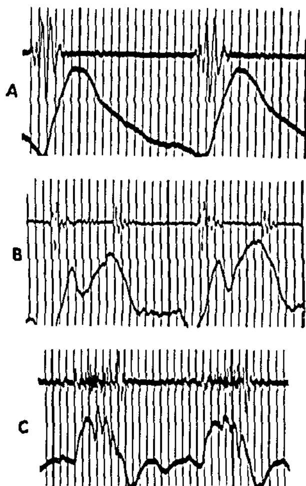


Fig 3-4. Tracings of aortograms recorded at the suprasternal notch with simultaneous phonocardiograms at apex A Atherosclerosis of the aorta (systolic aortic murmur at the base), normal large pulse. B. Aortic stenosis, anacrotic depression and late peak. C. Aortic stenosis; jagged top line of the pulse.

natural frequency of the aortic wall and by reflected waves from regions with sudden narrowings and branchings Experiments of Hamilton and Dow have proved that the pulse wave presents progressive changes so that it gradually acquires a higher peak and a simpler contour. This is due to the existence of a standing wave created by alternate accelerations and decelerations. The arch and the upper part of the descending aorta accommodate more blood during the first part of ejection, the lower aorta and its branches contain more blood during the second half. For this reason, the abdominal aortogram frequently has a more pointed peak and does not show the various details of the tracing as well Aortic catheterization in man has shown the following progressive changes: (1) The onset of the anacrotic limb occurs later and the anacrotic notch disappears. (2) The incisura is gradually lost and replaced by a dip ending in the dicrotic notch Both this and the dicrotic wave become more pronounced toward the periphery.

The aortogram is of use in the diagnosis of the following conditions: diffuse enlargement (aortitis) or local dilatations (aneurysms) of the ascending aorta and aortic arch due to syphilitic heart disease (second interspace and suprasternal notch); aortic stenosis (second interspace and suprasternal notch); coarctation of the aorta (abdominal aorta); and arteriosclerotic dilatation of the abdominal aorta (abdominal aorta) It is also used to differentiate between aneurysms and tumors or masses having a transmitted pulsation.

Tall pulsations are recorded in hypertensive or atherosclerotic patients with a systolic aortic murmur but no aortic stenosis (Fig. 3-4A). A typical tracing is obtained over the suprasternal notch in *aortic stenosis* The tracing presents an *anacrotic depression*, i e., a depression during the ascending phase (Fig 3-4B) or a *jagged* top line revealing a thrill (Fig. 3-4C) In aortic insufficiency, all aortograms reveal a tall pulse with an extremely rapid rise (*pulsus celer*, Fig. 3-5A).

TRACINGS OF THE CENTRAL PULSE

In addition to the aortogram, a typical "central pulse" may be recorded over the carotid and subclavian arteries

Hurthle was probably the first to record human carotid tracings He used a Marey tambour and a specially built support fastened to the patient's head A similar device was used shortly afterwards by Edgren Mackenzie used this method of investigation systematically Frank recorded carotid tracings optically, by connecting a funnel with a segment capsule Since then, numerous important studies have appeared Among them, those of Wiggers, Wezler, and Hamilton are outstanding Luisada has used a crystal microphone for recording these tracings since 1940

Technique. The tracing of the carotid artery is obtained by pressing a small funnel against the skin, medial to the right sternocleidomastoid muscle. The pulse of the subclavian artery is obtained by placing the funnel over the medial third of the supraclavicular fossa The funnel may be held steadily by hand or

may be fastened and held by a special device. A third method consists of wrapping around the neck the double cuff of a device for recording pulse and blood pressure. The cuff is inflated at 15 to 20 mm Hg in order not to embarrass cerebral circulation The tracing obtained by this method presents strong venous components. Still, it may be useful whenever the patient needs to move his arms and neck, as in taking simultaneous tracings of electrokymography and sphygmography.

Analysis of Waves. Tracing of the central pulse reveals three main waves (Fig. 3-5B). the *percussion wave* (*p*), the *tidal wave* (*t*), and the *dicrotic wave* (*d*). The details of the tracing are as follows:

1. One or two small waves are present during presystole and during the tension period of the ventricles.

2 There is a rapidly ascending phase (*the anacrotic slope*) which frequently presents a change of speed (*anacrotic depression*). The rise of the curve coincides with that large vibration of the first sound complex which is caused by opening of the aortic valves.

3. The peak or *summit* of the percussion wave is attained at about the middle of systole and is followed by a slight depression.

4. A second, more rounded wave (*tidal wave*) occurs during the second part of systole and is followed by the beginning of the descending phase (*catacrotic slope*)

5. In coincidence with the main vibration of the second sound complex (closure of the aortic valve), the curve presents a sudden drop or *incisura* (*i*) (Fig 3-5B), often followed by one or two *small vibrations.*

6 The curve rises again forming a slow positive wave, *the dicrotic wave.*

7. Later, the tracing gradually falls to its lowest level which is attained just prior to the rise of the following pulse wave.

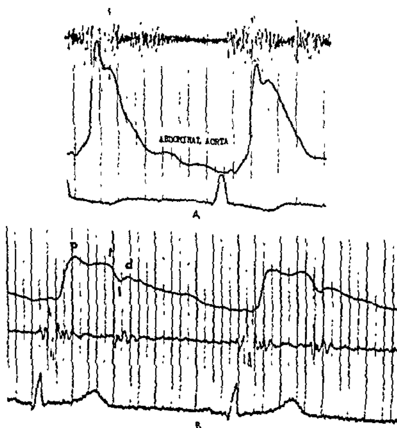


Fig 3-5 A Tracing taken on patient with aortitis and aortic insufficiency; large and rapid pulse recorded on the abdomen (*pulsus celer*); simultaneous phonocardiogram and electrocardiogram B Carotid tracing in a normal man· *p* = percussion wave, *t* = tidal wave; *i* = incisura; *d* = dicrotic wave; simultaneous phonocardiogram and electrocardiogram.

Reflected waves from peripheral subdivisions may be superimposed on the curve if this is taken at a high level of the carotid artery (upper carotid pulse); the changes are noticeable during early ejection, soon after the incisura They occur earlier if there is hypertonus or sclerosis of the wall, so that the speed of the pulse wave is increased. Low tonus of the wall is revealed by a high-peaked tracing.

The two small waves which precede the rise of the pulse curve are transmitted from the heart The first is caused by atrial contraction; the second, by bulging of the aortic valve during the tension period They are present only in the central pulse and are damped later by the walls of the peripheral arteries The rapid, ascending phase of the pulse curve is due to the ejection of blood into the aorta. The anacrotic change of slope is due to the fact that, at first, the inertia prevents a large displacement of blood while later a more rapid flow occurs, the tonic-elastic reaction of the aorta may also contribute to it The formation of a peak when about half of the blood has left the left ventricle may be attributed to the fact that the volume of blood entering the aorta is then smaller than that leaving the aorta through the various branches The tidal wave seems due to the summation of the still moving wave with multiple waves reflected from the periphery

The aorta and the left ventricle are still a single chamber at the beginning of ventricular diastole Ventricular relaxation causes a sharp drop of pressure in the aorta, which is quickly terminated by closure of the semilunar valves, this causes the incisura When pressure eddies complete the closure of the aortic valve, the retraction of the aortic wall forces blood toward the heart as well as toward the periphery This sets up a negative wave which follows the main percussion wave (*the incisura*) After closure of the aortic valve, the blood column rebounds from its surface and sets up a second, positive wave (*dicrotic wave*), which follows the main wave toward the periphery.

The tracing of the central pulse is useful mainly for timing the waves of other tracings For example, hepatic tracings or electrokymograms are frequently timed by means of a carotid tracing The tracing of the central pulse gives accurate information about the time of opening of the aortic valve (rise of the pulse) and its closure (incisura of the pulse). Therefore, this tracing presents interest in cases of bundle branch block. Abnormal patterns are found in atherosclerosis of the aorta, coarctation of the aorta, aortic stenosis, and aortic insufficiency. The tracing helps in the differential diagnosis of these conditions.

TRACINGS OF THE PERIPHERAL PULSE

History. The earliest studies of sphygmography (Vierordt, Landois) were made by using a loaded rubber bulb applied over the radial artery and were inaccurate. The first reliable instrument with mechanical registration was Marey's sphygmograph for recording the radial pulse. Dudgeon, Jaquet, and Frank and Petter used similar devices. However, another model with air transmission, writing through a Marey tambour, was somewhat superior. Tracings obtained through optical recording represent a second stage of development. Czermak pasted a small mirror over the skin in the immediate vicinity of an artery and recorded the motion of a beam of light reflected by it Frank and Ohm used mechanical-optical systems. However, in all these early systems the contact with the artery was not perfect and may have been a source of error For this reason, a new device was studied a pneumatic cuff was wrapped around the limb, pressure was set in the cuff and the tracing was recorded optically while the artery was submitted to a known compression (turgosphygmography) The best model for many years was that of Pachon and Boulitte. A third stage is represented by the use of a differential crystal microphone connected with a galvanometer and a blood pressure cuff (Rappaport and Luisada).

Technique. By means of the device of Rappaport and Luisada, the pulse tracing can be recorded on any of the four limbs, or any of their sections

The double cuff is carefully wrapped around the segment A pressure of 20 mm Hg is established in the lower, recording cuff The switch of the box is moved from "adjust" to "register," and further pressure is established in the upper cuff The tracing of the pulse can be taken at any compression It is advisable to note the level of compression, as well as that of the blood pressure in the limb prior to taking the record

Having already connected the jack of the instrument with the outlet of an electrocardiograph, the switch of the latter is moved to "1" (in a direct writing instrument this is not needed) and the record is taken at a film speed of 25 to 100 mm/sec Pulse recording is based on the use of a linear microphone with two outlets. Compression

is developed on both sides of the crystal, so that this is not damaged When communication between the two is closed, the pulsations of the artery, transmitted to the cuff, are received by one side of the crystal and transformed into electric pulsations The principle underlying the changes of contour of the pulse when pressure is increased in the upper cuff will be described later

A more peripheral sphygmogram can be obtained by the use of a *finger plethysmograph* of mechanical or electrical type (Fig 3-6).

Analysis of the Waves. The peripheral pulse of normal subjects is much simpler than the central pulse. The ascending phase is straight, the incisura is replaced by a rounded depression The dicrotic wave is also rounded. After the dicrotic wave, other secondary vibrations may occur.

The reaction of the peripheral arteries deepens the predicrotic notch transforming it into a valley, and rounds out the dicrotic wave. Therefore, the peripheral pulse shows no evidence of the tidal wave Care should be taken in regard to the compression of the artery. Figure 3-7 reveals how the contour of the pulse can be changed by compression.

The abnormal sphygmogram may show marked variations·

1. The *water-hammer type* has a steep, ascending slope and a rapid drop There is a turbulent condition at the front of the wave which may be revealed by a small anacrotic notch and is felt as a thrill upon palpation It is typical of aortic regurgitation

2. The *anacrotic pulse* has a notch in the ascending slope It is found in aortic stenosis, hypertension, and marked bradycardia

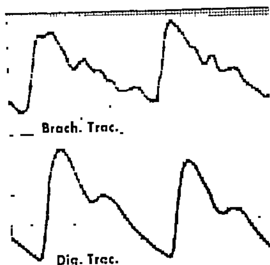


Fig. 3-6. Brachial and digital tracings of a normal person

3. The *dicrotic pulse* has a high dicrotic wave. It is found in fever, anemia, and hyperthyroidism.

4. *Pulsus alternans* is a regular pulse which has alternately one smaller wave out of two It is found in cases with severe myocardial damage.

5 *Pulsus paradoxus* is a severe periodical waxing and waning of the pulse connected with respiration and is typical of constrictive pericarditis

A measurement which seems to have a certain clinical value is that of *crest time*. This is measured in seconds between the rise of the pulse and the highest point of the main wave. Normal crest time of the radial pulse is between 10 and 16 per cent of the total dura-

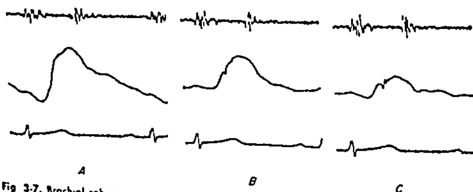


Fig 3-7. Brachial sphygmograms recorded in a normal adult with blood pressure of 95/55. The tracing at the left was recorded at a compression of 60 mm, the one in the center at 75; the one at the right at 90

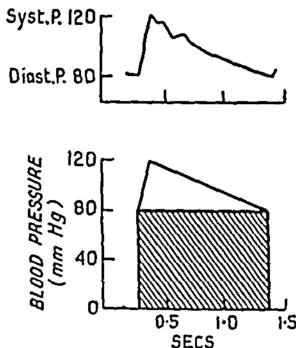


Fig. 3.8. The absolute sphygmogram.

tion of the pulse cycle, from rise of one pulse to rise of the next

The Absolute Sphygmogram. The sphygmogram or pulse tracing is a pressure tracing of the artery However, it does not reveal the pressure which is between zero and the foot of the wave A diagram, called the *absolute sphygmogram,* evaluates the various elements of the pulse (Fig 3-8) In this diagram, the ordinate represents *pressure* (measured by the sphygmomanometer) while the abscissa represents *time* and is based on the pulse rate

The sphygmogram can be used to yield several kinds of information

1 *Speed of the pulse wave* Simultaneous phonocardiograms (over the aortic area) and arterial tracings are recorded The distance between the second large vibration of the first sound (opening of the semilunar valves) and the rise of the pulse gives the speed of the wave if compared with the time lines of the record.

2. *Shape of the pulse wave.* Records should be taken at diastolic pressure, at mean pressure, and just below systolic pressure. The last shows prominence of all secondary waves, including the anacrotic notch. Measurement of crest time is made in tracings recorded at diastolic pressure.

3 *Study of arterial sounds.* This sound tracing is automatically recorded with the sphygmogram by using the apparatus described above.

4 *Irregularities of the heart.* Simultaneous electrocardiograms and sphygmograms are taken The former gives information about the type of arrhythmia, the latter shows the peripheral effect of the disorder.

5 *Study of the peripheral circulation.* The study of the arterial pulse may be important in cases of arteritis, thrombosis, or embolism The pneumatic cuff is successively applied to different sections of the limb, and the sphygmogram is recorded at the lowest pressure capable of giving a good record Crest time is measured in both the tracing of the medium-sized arteries and in that of fingers and toes.

6 *Measure of stroke volume.* A method for calculating stroke volume on the basis of the study of the pulse was described by Wezler and Boeger It was further studied by Altana, Grishman and Master, and Schmid and Reubi The method is, so far, not accurate, as revealed by the following quotation. "The old adage about lifting oneself by one's own bootstraps might be applied to many such attempts" (Peterson, 1957)

5

Sphygmomanometry

BLAS MOIA

Sphygmomanometry is the method used for measuring the systemic arterial pressure. It is common to register the levels of both the systolic and the diastolic pressure, calling the difference between them "pulse pressure" (hence the name "sphygmomanometry") or "differential pressure." The *mean arterial pressure* can also be measured or calculated. There are two methods of measurement, direct and indirect.

DIRECT METHODS

In order to make a *direct measurement*, it is necessary to insert a *needle* or *cannula* into an artery and connect it with a manometer, thereby making it possible to measure the pressure of any artery which is accessible to the observer.

Hales (1733), not possessing a manometer, calculated blood pressure by measuring the height to which a column of blood rose in a vertical tube which was connected to the femoral artery of a horse. Almost 100 years later, Poiseuille (1828) simplified the method and described *the mercury manometer* with a U tube. Ludwig later added to this a metal arm with an attached float which rested over the meniscus of mercury; this permitted the recording of the movements and changes in height of the column on a revolving drum, as is commonly done in physiology laboratories. These manometers can be used for measurement of *mean pressure*; due to marked inertia, they give inaccurate results (too low for the systolic pressure, too high for the diastolic pressure).

The perfecting of *optical manometers* allowed numerous investigators, especially Hamilton et al., to remedy the above disadvantages, obtaining accurate results in the direct *registration* of recording human blood pressure. Nowadays we have at our disposal any number of excellent *electromanometers* and *strain gages*. Thanks to them, the direct measurement of arterial pressure *in man* by puncture of the arteries of the upper or lower limbs has become a common procedure in all laboratories where hemodynamic studies are made. However, for ordinary clinical use, indirect methods are usually preferred since their application is much simpler and gives fairly good results. Indeed, by employing ordinary techniques, indirect methods, especially the auscultatory, allow an average error of ±8 mm. Hg in normal individuals for either the systolic or diastolic pressure. These differences appear to be more marked, however, as the arterial pressure rises, especially in young hypertensive individuals. The indirect methods also have the drawback that they can only be applied to the measurement of arterial pressure in the extremities.

INDIRECT METHODS

Although formerly there had been numerous ineffectual attempts at instrument measurement of arterial pressure in man, only after the introduction of the pneumatic cuff by Riva-Rocci did the indirect method begin to show security and certainty of results.

Palpatory Method of Riva-Rocci

The original procedure of Riva-Rocci was extremely simple. A pneumatic cuff connected to a manometer, which registers the pressure in millimeters of mercury, is applied around a limb and is inflated until the pulse disappears. The moment that the finger palpating the artery below the compression perceives the reappearance of the pulse indicates on the scale of the manometer the level of systolic arterial pressure. Using a manometer with a column of mercury, the level of systolic pressure corresponds to the point on the scale of

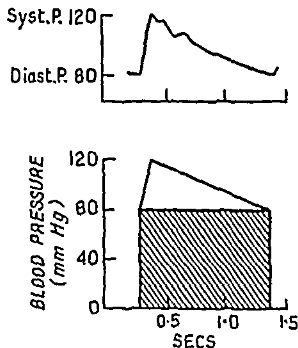


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4. *Irregularities of the heart* Simultaneous electrocardiograms and sphygmograms are taken. The former gives information about the type of arrhythmia; the latter shows the peripheral effect of the disorder.

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resulting from rapid changes in velocity By this, we can explain the pistol-shot sounds which appear spontaneously or when the cuff has been completely deflated (*so-called zero diastolic pressure*) *in aortic insufficiency* and *in conditions associated with high cardiac output. Thus also explains the absence of the Korotkov sounds in the presence of normal or reduced pressure (direct measurement)*, such as that of certain states of shock with low cardiac output However, in these cases, the patient himself may perceive sensations beneath the cuff while this is being deflated and may give a fairly accurate measure of both systolic and diastolic pressure. Usually, *in the moment corresponding to systolic pressure, the patient feels the appearance of arterial pulsations beneath the compressed cuff.* These pulsations continue to become more intense and easily perceived as the decompression progresses until a given moment, *when they become attenuated and suddenly are no longer felt. This point corresponds exactly to the disappearance of the auscultatory sounds and reveals consequently the diastolic pressure*

Finally, when none of the indirect methods can make it possible to register the arterial pressure in the upper limbs, as in the aortic arch syndrome (or pulseless disease), an approximate idea of the systolic pressure may be gathered by using a modification of Gaertner's method The cuff is placed on the arm in the usual manner, then the arm is elevated to a vertical position and the cuff is inflated The arm is then returned to the horizontal position and the cuff is slowly deflated The moment in which a flush first appears in the forearm indicates approximately the mean arterial pressure of the arm.

Oscillometric Method. This method is not as practical as the auscultatory, since it does not usually permit a precise determination of the moment in which changes in the amplitude of the oscillations occur Nevertheless, the values of the mean arterial pressure can be obtained with fair accuracy This is useful in measuring pressure in the lower limbs and for recognizing disturbances in the blood flow of the arteries

Pachon, following ingenious observations of Marey, devised an apparatus which is still used today, called the *oscillometer* An aneroid capsule which receives pressure variations from the cuff is placed inside a hermetically sealed metal box which also receives the pressure variations of the cuff. By this method, the pressures on both surfaces of the aneroid capsules are balanced When the connection which transmits pressure from the cuff to the metal box is interrupted, the aneroid capsule receives only the differences in the pressure of the pulse, which vary according to the degree of counterpressure induced in the cuff Such oscillations may be read or may be graphically recorded

When the pressure of the cuff is above the systolic pressure, the needle which registers the movements of the aneroid capsule remains practically still When the cuff is deflated, nearing the systolic pressure, small oscillations, called *supramaximal*, appear, these are produced by the pulse waves which beat against the cuff At the moment *when the first pulse wave achieves passage below the cuff, one may observe an abrupt definite increase* in the amplitude of these oscillations, this increase marks *the systolic pressure* As the deflation progresses, the amplitude of the oscillations *increases* to a maximum and then begins to diminish The moment of *maximum amplitude* of the oscillations corresponds to the *mean pressure, not to the diastolic* pressure, as was erroneously *supposed* by Pachon MacWilliam and Melvin have demonstrated experimentally that the *reading of the diastolic pressure corresponds to the point at which the amplitude of the oscillation shows a sharp attenuation or ceases abruptly during the process of deflation.* Unfortunately, this brusque *transition* between the zone of large and small *oscillations* does not always exist or is *not always easy* to perceive Therein lies the difficulty in reading the diastolic pressure by this method, *even though* one may use modern instruments

The diversity of criteria employed by different authors for the reading of the systolic and diastolic pressures in both methods, auscultatory and oscillometric, does not allow one to draw conclusions *as to* their comparative merits. Nevertheless *it is evident* that, when correct techniques *are used*, the results are practically equal Furthermore, the oscillometric method *has the advantage* that, with special apparatus an *oscillographic* curve may be graphically *recorded*, thereby allowing for comparative studies

In the apparatus devised by Rappaport and Luisada (Chap 4, Graphic Study of Pulse), a double-chambered pneumatic cuff (pressure chamber and recording chamber) is used, and two differential crystal microphones permit the

the apparatus at which the meniscus of the pulsating column becomes convex.

The palpatory method of Riva-Rocci, in spite of its extraordinary usefulness, unfortunately does not permit the determination of the diastolic pressure. Nevertheless, Ehret, supported by the observations of Strassburger, proposed measuring the diastolic pressure by palpating the brachial artery below the pneumatic cuff and reading the column of mercury at the moment of the sudden disappearance of the ample and vibrant pulsations; this occurs when the cuff is deflated below diastolic pressure and the pulse again presents normal characteristics. This method, which is recommended by French authors, has been rapidly forgotten with the common use of auscultatory and oscillometric methods.

Auscultatory Method. Korotkov, auscultating the brachial artery below the pneumatic cuff, noted that, as the cuff is deflated, clearly audible sounds appear as soon as the arterial collapse disappears. This indicates that the systolic pressure has been reached. As the decompression of the cuff continues, the sounds increase in intensity and change in character until there is a marked and sudden diminution of their intensity which, with further deflation of the cuff, continues until total disappearance.

In spite of the fact that "any systematic classification of the characteristics presented by the sounds as the deflation is carried out, becomes artificial, arbitrary, and hardly applicable to any given case," it is still considered true that five different phases may be differentiated during this procedure. The average duration of each phase in millimeters of mercury in an individual whose arterial pressure is 130/85 mm (consequently, with a pulse pressure of 45 mm) would be as follows (Goodman and Howell): (1) initial thumping sounds (14 mm), (2) murmuring sounds (20 mm), (3) clear, sometimes bell-like, sounds (5 mm), (4) dull and muffled sounds (6 mm); (5) disappearance of sounds. Korotkov and other authors of his time agreed that the reading of the diastolic pressure should be made *at the moment of total disappearance of the sounds* (that is, between the 4th and 5th phases). However, MacWilliam et al., Fischer, and later the majority of authors, considered that the reading of the diastolic pressure should be taken instead *at the moment at which the 3d phase passes to the 4th, i.e., when an abrupt diminution of the intensity of the sounds occurs.*

In its first report (1939), the *Committee of the American Heart Association* recommended considering as the diastolic pressure not only this point, but also the point of total disappearance of sounds and noting both figures when a difference existed. Later, another *Committee of the American Heart Association* (1951) stated that the best indication of diastolic pressure is that point at which all sounds disappear. The point of muffling would only indicate the diastolic pressure in those hemodynamic circumstances in which there is no complete disappearance of sound. However, it is important to remember that this condition is sometimes provoked or favored by the application of too much pressure with the stethoscope while listening for the sounds, or by too tight wrapping of the cuff.

In spite of the objections of Roberts et al. and van Bergen et al., founded on a comparative study of the results obtained by direct and indirect methods, the author believes that the above-mentioned criterion of the Committee should be accepted as definite.

One of the arguments against it is that, in certain circumstances, such as cases of aortic insufficiency, the sounds may still be heard even though the cuff has been completely deflated. Nevertheless, the investigations of Lange et al. demonstrated that, in these conditions, the sounds produced by the deflation have, added to them, the "pistol-shot" sounds which can appear spontaneously in large arteries, as pointed out by Gittings.

In order to explain these sounds, as well as those heard during the deflation of the cuff, the following explanations have been offered: (1) sudden expansion of the arterial wall caused by the pulse wave, (2) the "water-hammer" effect, (3) the "preanacrotic phenomenon", and (4) the "Bernoulli effect" (Lange et al.).

By placing a microphone above or below the site of arterial puncture and directly recording pressure variations, it has been proved that each sound precedes the rise in pressure and the lateral movement of the vessel by 10 to 12 msec and that the sound vibrations are propagated along the artery at a velocity of 8 m/sec, in strict relation with the propagation of the pulse wave. This suggests that the pistol-shot sounds, as well as the Korotkov sounds, are related to peri

method should be noted and mentioned as such.

The systolic pressure which is found by inflating the cuff until the sounds disappear is usually much lower than the actual pressure On the other hand, it is often much easier to find the diastolic pressure by inflating the cuff until the first sounds are heard. Often, by this method, sounds may be heard which could not be heard by utilizing the method of decompressing the cuff from the systolic pressure downwards In such cases, the values found by the former procedure should be recorded.

When the pressure is measured for the first time, it is advisable to do it in both arms and then to palpate the femoral pulse, although it would be preferable to measure also the pressure in the lower limbs. The figures of arterial pressure obtained in the supine position are usually equal to or lower than those registered in a standing or sitting position However, Currens studied 1,000 healthy adults (25 to 55 years) after assuming the erect position for 3 min, he found an increase or decrease of 10 mm or *more in the* systolic pressure in 3.7 and 32 8 per cent respectively; no appreciable changes in 73 5 per cent, and an increase or decrease of 4 mm or more in diastolic pressure in 48 3 and 12 0 per cent respectively with no changes in 39 7 per cent. Consequently, it is advisable to note in which position the pressure reading was made The author recommends measuring the pressure *both in* a supine position and standing, with the arm in a horizontal position, especially in patients who have been treated with the modern hypertensive drugs

In order to measure *the pressure of the lower limbs*, it is better to have the patient lie face down, placing the cuff around the lower part of the thigh and the stethoscope in the popliteal space. However, the same results may be obtained by having the patient lie in dorsal decubitus, in this position one can also obtain satisfactory results by placing the cuff on the lower part of the leg and placing the stethoscope over the dorsalis pedis artery. Frequently, however, the values are somewhat lower in this segment than in the arm, especially for the systolic pressure.

Measurements by the auscultatory method in the lower limbs are not always made easily; *therefore*, it is often preferable to use the oscillometric method

Kotte et al., utilizing bags 15 5 cm wide, observed that the auscultatory values of systolic and diastolic pressures in the thigh are always higher than those obtained by the direct method or by puncture of the femoral artery, the difference being much greater in patients with aortic insufficiency. Later measurements of the arterial pressure by the direct method showed that the systolic pressure may be from 10 to 40 mm Hg higher in the thigh than in the arm, but that the diastolic pressure is essentially the same. Consequently if, with a given sphygmomanometer, the diastolic pressure is greater in the thigh than in the arm, it is evident that incorrect results have been obtained probably because the width of the cuff was inappropriate.

graphic recording of the arterial pulsations simultaneously with the sounds of Korotkov.

Lately, several ingenious instruments have been described which permit the continuous recording of the arterial pressure by the auscultatory method. One of them is that of Rose et al., which gives the values for diastolic and systolic pressures. Another is that of Endres et al., which operates by attaching the microphone to a finger, it is very useful in surgical procedures and gives continuous values for the systolic pressure and possibly also for the mean arterial pressure.

RULES FOR MEASURING ARTERIAL PRESSURE

In order to obtain correct and comparative recordings of the arterial pressure by indirect methods, especially the auscultatory, it is necessary to observe certain fundamental precautions. Some depend on the apparatus used, others on the conditions of the patient and of the observer. There is no special advantage in either aneroid or mercury manometers, as long as they are of good quality and are periodically checked for correct functioning.

The characteristics of the inflatable bag and of the cuff which covers it are of extraordinary importance. Von Recklinghausen had already noted that when using the cuff 5 to 6 cm wide proposed by Riva-Rocci, the reading of the systolic pressure was significantly higher than when using a 12-cm cuff Generally speaking, it is advisable that the inflatable bag be "20 per cent wider than the diameter of the arm or thigh on which it is to be used."

The bags usually employed have the following widths: 18 and 12 cm for thighs and arms of adults, respectively, 8 or 9 cm for children younger than 8 years of age, 5 or 6 cm for children less than 4 years old, and 2.5 cm or less for infants below 1 year of age.

It is absolutely necessary that the cuff be made of nonstretch material which, once applied to the limb, will exert equal pressure on the whole surface. Otherwise, the inflation of the bag would produce bulges or displacements and the pressure applied on the artery could be reduced, giving the same effect as a bag of less width In this respect, the use of the newer clip-on cuffs should be recommended For the same reason, the cuff should be applied snugly around the extremity After applying the cuff tightly and then loosening it so that its circumference was extended 3 1 cm, Nuessele observed a mean pressure increase of 8.1 mm for the systolic pressure and 9 3 mm for the diastolic. The differences were more marked in individuals of normal or increased weight than in thin persons

If the bag does not encircle the entire limb, one should attempt to place it in such a way that its central part is that which compresses the main arterial trunk.

While reading the pressures, the bag should be inflated rapidly in order to avoid the production of a marked distal venous congestion, since this will make the perception of the sounds more difficult and will facilitate the appearance of an *auscultatory gap*. This curious phenomenon consists of the disappearance or fading of the 2d phase of the sounds of Korotkov and might give rise to error if the reading is made too rapidly and attention has not been paid to the sounds of the 1st phase The French authors called attention to the frequency of this phenomenon in cases of aortic stenosis, but it may also be found in patients with arterial hypertension and can be observed in cases of arteriosclerosis, heart failure, severe bradycardia, and other conditions

Rodbard and Ciesielski have proved that, in aortic stenosis, "the cuff pressure at which the gap occurs corresponds exactly to the level of the incisura on the ascending limb of the arterial pulse wave. . . . If there is any sign of auscultatory gap, the observation should be repeated by filling the cuff when the arm is upraised "

It is always recommended that several successive determinations of the arterial pressure be made at the same sitting in order to minimize the influence of the *emotional status*, causing a possible increase in the tone of the arterial wall. In order to avoid *venous congestion*, the cuff should be completely deflated each time that the blood pressure is taken.

The reading of systolic pressure should be made by inflating the cuff to a pressure higher than systolic and then noting the level at which the first sounds (auscultatory method), or the first pulsations (palpatory method) appear Usually the systolic pressure obtained by the auscultatory method is slightly higher than that found with the palpatory method. If the reverse should occur and careful readings by the auscultatory method do not change the situation, the value obtained by the palpatory

method should be noted and mentioned as such.

The systolic pressure which is found by inflating the cuff until the sounds disappear is usually much lower than the actual pressure. On the other hand, it is often much easier to find the diastolic pressure by inflating the cuff until the first sounds are heard Often, by this method, sounds may be heard which could not be heard by utilizing the method of decompressing the cuff from the systolic pressure downwards. In such cases, the values found by the former procedure should be recorded

When the pressure is measured for the first time, it is advisable to do it in both arms and then to palpate the femoral pulse, although it would be preferable to measure also the pressure in the lower limbs The figures of arterial pressure obtained in the supine position are usually equal to or lower than those registered in a standing or sitting position However, Currens studied 1,000 healthy adults (25 to 55 years) after assuming the erect position for 3 min, he found an increase or decrease of 10 *mm or more* in the systolic pressure in 3.7 and 32 8 per cent respectively, no appreciable changes in 73 5 per cent, and an increase or decrease of 4 mm or more in diastolic pressure in 48 3 and 12 0 per cent respectively with no changes in 39 7 per cent. Consequently, it is advisable to note in which position the pressure reading was made The author recommends measuring the *pressure* both in a supine position and standing, with the arm in a horizontal position, especially in patients who have *been treated* with the modern hypertensive drugs

In order to measure *the pressure of the lower limbs,* it is better to have the patient lie face down, placing the cuff around the lower part of the thigh and the stethoscope in the popliteal space However, the same results may be obtained by having the patient lie in dorsal decubitus; in this position one can also obtain satisfactory results by placing the cuff on the lower part of the leg and placing the stethoscope over the dorsalis pedis artery. Frequently, however, the values are somewhat lower in this segment than in the arm, especially for the systolic pressure.

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Kotte et al, utilizing bags 15.5 cm wide, observed that the auscultatory values of systolic and diastolic pressures in the thigh are always higher than those obtained by the direct method or by puncture of the femoral artery, the difference being much greater in patients with aortic insufficiency. Later measurements of the arterial pressure by the direct method showed that the systolic pressure may be from 10 to 40 mm Hg higher in the thigh than in the arm, but that the diastolic pressure is essentially the same. Consequently if, with a given sphygmomanometer, the diastolic pressure is greater in the thigh than in the arm, it is evident that incorrect results have been obtained probably because the width of the cuff was inappropriate.

Measurements of venous pressure

Phlebomanometry

BLAS MOIA

Dynamic Measurements

WILLIAM M. HITZIG

PHLEBOMANOMETRY

Phlebomanometry is the measurement of *mean venous pressure* In clinical practice, it is determined by using superficial veins, usually in the antecubital fossa, but such measurement may be made in any part of the body, especially if a localized venous obstruction is suspected and one wishes to make comparative studies between veins of different collecting systems

In order to make *direct measurements* of venous pressure, it is necessary to puncture the vein and connect the needle directly with a manometer. Numerous *indirect methods* have been proposed with the purpose of avoiding venous puncture They attempt to measure the pressure necessary to collapse the vein Detailed descriptions of these methods, which have only a historical interest, can be found in a monograph by Villaret et al.

An approximate idea of the venous pressure can be obtained without instruments through *Gaertner's maneuver*. the patient is placed in a sitting position, the arm of the patient is slowly raised and note is taken of the level above the fifth rib (or zero level) at which the veins of the hand spontaneously collapse However, the results of this maneuver are somewhat variable Of greater value is *Lewis' procedure*, which consists of placing the patient with his head on a pillow at different levels and measuring the distance from the point where the venous engorgement of the external jugular ends to the anterior surface of the manubrium of the sternum. Normally, both levels coincide or there is a minimum difference.

Since these changes may not be easy to determine, in the neck as well as in the hand, it is necessary to use the direct venous puncture, as proposed by Hales in animals, and by Moritz and von Tabora in man

The technique consists of puncturing a superficial vein by introducing a needle through the skin and connecting it to a manometer which measures the pressure in centimeters of water (or blood). By this method one determines the lateral venous pressure, and there is no basic difference in the readings if the opening of the needle is pointing in the same direction as the blood flow (as is usual) or against the current.

Numerous authors have proposed different modifications of the original method of Moritz and von Tabora, these usually consist of changes in the intermediate connections and in the type of manometer to be used There is no advantage in using one or the other type of manometer, as long as its calibration is correct. Aneroid manometers can be used instead of glass tubes calibrated in centimeters It is advisable to prevent coagulation of the blood in the manometer by washing the system with a sterile solution of heparin Then, the blood is allowed to rise in the tube and the height of the column is read in centimeters Another method is to first fill the manometer with a sterile normal saline solution, preferably containing sodium citrate, and allowing the column to descend until a steady level of pressure is reached

A popular method of measuring venous pressure is that of Winsor and Burch. This permits the use of needles of small caliber, but is somewhat more complicated, since a pressure bulb is interposed between the needle attached to an observation tube and the water manometer The pressure which is applied on the bulb in order to immobilize the meniscus of venous blood, which passes through the needle and is observed in the observation tube, produces a rise in the manometer to a height equivalent to the venous pressure.

Actually, the most difficult and arbitrary factor of any of these methods is the determination of the *zero reference-level* in order to eliminate the hydrostatic factor.

Based on the erroneous concept that the peripheral venous pressure is always a faithful reflection of the pressure variations of the right atrium, attempts were made to use the level of the right atrium as the zero reference-level Usually, with the patient in dorsal decubitus, the right atrium is considered to be located at *one-third of the distance between the anterior aspect of the chest and the dorsal plane at the level of the fourth intercostal space* However, Lyons et al consider that it is more proper to place it at 10 cm above the table on which the patient is resting, because the position of this chamber will vary less with respect to the posterior structures of the chest than with the anterior Holt tries to be more precise by making two successive readings, one with the patient in dorsal decubitus and one in ventral decubitus

Winsor and Burch introduced the concept of phlebostatic axis and phlebostatic levels. The *phlebostatic axis* is defined as a line which connects a transverse plane of the body passing through the point of union of the lateral border of the sternum and the fourth intercostal space and a frontal plane of the body passing through a midpoint of the anteroposterior diameter of the chest The *phlebostatic level* is defined as any horizontal plane which passes through the phlebostatic axis This is supposed to be of practical use in the calculation of the venous pressures in different positions of the body

Whatever the point of reference used, the normal pressure in the veins of the antecubital fossa varies between 50 and 150 mm of water with a range of 300 per cent. Likewise, the gradient between the cubital veins and the right atrium varies from 12 to 76 mm of water. "A sixfold spread of gradient cannot be explained by differences in resting blood flow but might well be due to the varying resistance of more or less collapsed veins (Landis et al.).

Previous observations by Duomarco et al. and by the author demonstrated that Landis' opinion is true, but should be further elaborated In this respect, Duomarco et al. (Part 2, Chap 19) demonstrated that the subclavian vein undergoes a physiological collapse as it enters the thorax due to the passage from an environment subjected to the atmospheric pressure to one of negative pressure This venous collapse does not create an obstacle to the free entry of blood into the thorax, but impedes the propagation of the pleural suction to the contents of the peripheral veins This explains why only exceptionally can one detect in the veins of the arm the inspiratory fall in pressure which always occurs in the right atrium and the large veins of the thorax in persons without cardiac insufficiency (Moia et al.).

An elementary principle of physics demonstrates that, when the pressure is measured in a collapsible tube which passes from the atmosphere to a chamber of low pressure, the pressure gradient in the part of the tube which is subjected to the atmospheric pressure ends at the orifice of penetration into the chamber and, therefore, is independent of the degree of low pressure within this chamber.

The subclavian collapse which interrupts the hydraulic continuity between the veins of the arm and the right atrium is anatomically located at the level of the suprasternal notch, which is the reference point suggested by Lewis If there is no heart failure or the latter is of a moderate degree, so that right atrial pressure is not sufficient to distend the thoracic veins and reestablish a hydraulic continuity with the whole system, the following statement should be considered correct. "the venous pressure in the antecubital fossa measures only the height of the subclavian collapse, somewhat modified by the effect of a number of muscular actions and therefore not influenced by the degree of thoracic negative pressure nor by the pressure or position of the right atrium within the chest."

Gauer and Sieker attempted to eliminate this thoracic venous collapse by placing the patient in right lateral decubitus with the right arm hanging perpendicularly By this maneuver, a hydraulic continuity is reestablished between the veins of the arm and the right atrium and the waves of the venous pulse are easily de-

tected in the veins of the arm. Using as zero reference-level the midpoint of the lateral thoracic diameter at the fourth rib, they found in 15 normal subjects a peripheral venous pressure which varied between 25 and 31 mm of water.

The enormous variation in pressures which has been found, even utilizing the latter procedure, demonstrates that, in addition to the above-mentioned physiological collapse of the thoracic veins, other factors must intervene which contribute to the independence of the peripheral venous pressure from the pressure of the right atrium.

By taking venous pressure measurements in man through segmental catheterization and recording the pressure at various intervals from the right atrium to the antecubital fossa, the author has demonstrated that *the structures of the axilla usually compress to some degree the veins passing through it*. This compression, contrary to the previously mentioned collapse, produces *resistance* to venous flow. By this mechanism, the distal venous pressure is increased in the same way as when a tourniquet is applied to the arm. From this, one gathers that, in order to measure accurately the venous pressure, it is necessary to obtain a maximum degree of muscular relaxation. The author has observed that, in normal individuals with increase of peripheral venous pressure, the pressure in the cubital vein may fall notably without any modification of right atrial pressure after intravenous injection of a small dose of Pentothal.

These same mechanisms of extrinsic compression by different structures of the body are probably responsible for the marked differences in venous pressure which exist normally in different segments of the body. Otherwise, there would be no explanation for the fact that the measurements made by Ochsner et al. show that the venous pressure may be higher in veins nearer the heart than in those farther away. It is necessary to keep these findings in mind when comparative studies of the venous pressure in different regions of the body are made, in order to try to discover localized venous obstructions. On the other hand, Burch, 1951, and others, believe some of these variations in peripheral venous pressure are connected with modifications of the *venomotor tone*. This would explain (as Petrány et al. have suggested) the inspiratory rise of venous pressure in the arm of individuals without heart failure. However, as various structures of the chest, which are capable of compressing the venous system at its entrance into the thorax, are put into tension during inspiration, it is easier to explain the modification through this mechanism.

These facts which have just been mentioned explain why, even when using the suprasternal notch as zero level, the peripheral venous pressure may vary a great deal in normal individuals. On the other hand, *when there is heart failure with marked hypertension of the right atrium and thoracic veins, this would overcome the obstacle at the axilla and would reestablish the hydraulic continuity of the whole venous system. Thus, inspiration would be accompanied by a marked acceleration of flow.*

It may then be gathered that, in patients without heart failure or with minimal insufficiency, the venous pressure of the antecubital fossa does not follow the variations in pressure of the right atrium. Therefore, venous pressure measurements will reveal heart failure only if this is severe.

On the other hand, the method may be of great value through the use of certain procedures which provoke a rapid increase in venous pressure, such as pressing the abdomen, raising the lower limbs, and giving an intravenous infusion. Since it is the simplest and most innocuous method, the author prefers compressing the abdomen, especially the lower quadrants, since sometimes the upper quadrants are tender as a result of congestion of the liver on account of heart failure.

In patients without cardiac failure, forceful pressure over the abdomen (as long as the subject continues breathing normally and does not hold his breath so as to produce a Valsalva maneuver) *does not raise the venous pressure at the elbow by more than 2 cm of water, and may even decrease it* due to the fact that pressure over the abdomen may partially obstruct the inferior vena cava. This is due also to the fact that the inferior vena cava, which at its origin has a pressure equal to that of the abdominal cavity, *collapses* when it passes through the diaphragm and enters into the low-pressure chamber of the chest; therefore, normally there is an interruption between the sec-

tion influenced by thoracic variations and that affected by abdominal variations This blocking effect disappears when right atrial hypertension develops because the pressure of the thoracic portion of the inferior vena cava then overcomes that of the abdominal segment. "In such a circumstance, the constantly engorged venous system acts as a rigid tube, full of liquid, which transmits pressure variations in all directions, whether these variations be thoracic, abdominal, or intravascular." (Duomarco et al.) In other words, the same phenomena which apply to the subclavian vein are also true for the inferior vena cava

Numerous authors, including the present one, have proved that, in right heart failure, the venous pressure of the elbow usually rises *more than 2 cm of water* during abdominal compression It is *interesting to note that, in patients with heart failure in whom treatment* has produced a disappearance of edema and *hepatomegaly, abdominal pressure continues to produce an abnormal rise in peripheral venous pressure* This explains the *hepatojugular reflux* of the French authors, in which it may be observed that, at the same time that the venous pressure rises, the external jugular veins become more engorged and the height of the venous column within them also rises. Similar changes may be observed at the end of a deep inspiration. The author has *also seen* that, in these conditions, there is a diminution of the amplitude of the jugular pulsations, even in cases of tricuspid insufficiency. The systolic collapse of the venous pulse may also *disappear* and be *substituted by a positive venous pulse (Moia)*.

When venous pressure is only slightly elevated, and abdominal *compression causes* a rise of less than 2 cm of water, *does not increase venous* engorgement, and fails to change the type of venous pulsations, *one can almost certainly rule out the existence of right heart failure*. The *opposite* is also true, and *this explains* the clinical importance of *practicing the maneuver* of abdominal compression in all cases where heart failure may be suspected

DYNAMIC MEASUREMENTS

Venous pressure values within *certain limits* (4 to 8 cm ±3 to 10 cm) represent *a normally* functioning right ventricle. *Wider variations* have been observed by Hussey (4 to 12 cm), by Lyons et al, and by Winsor and Burch (5 to 14 cm). Marked depression of the *venous pressure* (0 to 2 cm) usually signifies *a diminished venous return*, as is found *in peripheral* failure or shock *Elevation* of the systemic venous *pressure* (11 to 30 cm) is regarded as a *cardinal sign* of *right heart failure* However, unless clinical or laboratory methods are utilized, *incipient or* lesser disturbances of *right* ventricular function *may* remain unrecognized, because in such *cases* the initial pressure in the veins may *overlap* the values recorded for both early right heart failure and for the limits of upper normal From this, it is apparent that isolated or "static" *measurement* of venous pressure in *systemic veins is* probably not sufficiently revealing.

The great bulk of the recorded data concerns the venous pressure determination in cardiac patients under basal conditions The inadequacy of the "static" methods of measuring the venous pressure at rest becomes even more apparent in those rare cases of frank right heart failure where, despite the *persistence of the classical* clinical manifestations *of right ventricular* insufficiency, a normal or *nearly* normal *initial* venous pressure is encountered at rest. This is not only true *in incipient* right heart failure, but occasionally *also* in patients with *markedly* advanced cases whose *treatment* with diuretics and digitalis had *significantly* altered the ratio between the *circulating* blood volume and the total venous *capacity* to yield a normal initial venous *pressure* at rest. *In such* cases, only the "dynamic" *measurements* of the venous pressure obtained by [illegible] *exe*[illegible] mu[illegible] can confirm in a physiological way the presence *of* lesser or greater disturbances of the *functional* reserve of the right heart

The functional reserve of the right heart *is*, *roughly speaking*, directly *proportional* to *its capacity* to cope with an increased venous *return*. This explains the absence of a cardiac reserve in patients with *frank* right heart failure revealed by exercise or rapid intravenous

fluid administration. In such instances, the increased venous return engendered by effort or rapid venoclysis is accompanied by an *increased elevation of the systemic venous pressure,* as well as by exaggeration of the clinical symptoms.

The results obtained with "dynamic" methods for measuring the venous pressure following both exercise and intravenous fluid administration have been carefully tabulated *Exercise* increases the venous pressure in normal subjects, but as a rule, depending upon its severity, the venous pressure returns to a normal or a lower level within a minute after its cessation (Szekely) In the presence of heart failure, exercise elevates the venous pressure to a much higher level, and the return to its previous level is more gradual. Similarly, a *venoclysis* of 500 to 1,500 ml of normal saline or of 5 per cent glucose solution may cause a significant elevation of the venous pressure in normal and abnormal circulatory states, but its differential value lies in the rapidity or slowness of return of the elevated venous pressure to its former level. Even in normal subjects, a significant increase in venous pressure may persist if more than 20 ml of fluid/min is administered intravenously

Exercise and *venoclysis,* as the "dynamic" means for measuring the functional reserve of the right heart, offer technical difficulties and may cause untoward physiologic disturbances, especially in cardiac patients, these factors eliminate them from routine use Instead, a simple clinical method for recording the ability of the right heart to cope with an increased venous return has been found satisfactory. It adapts the principles enumerated above and is based on a simple maneuver which employs visual inspection and palpation of the external jugular vein before and during *maintained compression of the upper abdomen.*

The basis of this clinical and manometric determination of venous pressure is a sign described by Pasteur and by Rondot, who found that manual compression of an engorged liver causes swelling of the veins in the neck. Pasteur regarded it as a phenomenon associated with tricuspid regurgitation but Rondot, who realized its broader implications, correctly attributed it to weakness of the right ventricle and called it *hepatojugular reflux.* Later, *Plesch also applied this sign to clinical cardiology* and concluded that its presence (positive "hepatojugular reflux" phenomenon) indicated right ventricular insufficiency.

Hitherto, observations on the fullness of the cervical veins during this Pasteur-Rondot maneuver were confined solely to cases in which there was frank failure of the right side of the heart. Observations and careful correlation of the state of the cervical veins in health and in lesser grades of right ventricular insufficiency have been convincing evidence that this clinical sign has equal value in the clinical differentiation of normal and abnormal circulatory syndromes at the bedside. Thus, *a negative "hepatojugular reflux" phenomenon* significantly implies that the functional efficiency of the right ventricle, under the conditions of a limited increase in the venous return, is still intact and that the presenting symptoms which mimic heart failure are not of cardiogenic origin.

A greatly simplified direct method for recording, not only the venous pressure, but also its clinical counterpart (the "hepatojugular reflux" phenomenon), is the method proposed by Taylor et al, slightly modified by Fishberg and Hitzig.

The apparatus consists of an L-shaped tube of 4-mm bore, the tip of the short limb being ground to fit an intravenous needle, while the long limb is graduated in centimeters The procedure is carried out as follows:

The manometer and the attached needle, which is 18 gage, are first moistened with a 10 or 30 per cent citrate solution in order to inhibit blood clotting and to minimize the resistance of the flow of blood in the tube. In this way, the sensitivity of the manometric system can be maintained and protracted measurements for recording the venous pressure curve are more readily carried out. After the subject reclines, a large antecubital vein is selected. The arm is leveled 5 cm beneath the anterior chest wall at the insertion of the fourth rib (the assumed *zero reference point*), which should correspond theoretically to the level of the caval openings A tourniquet, preferably a loose blood-pressure cuff, inflated to from 40 to 60 mm, is applied to the arm After the skin is cleansed with alcohol, an 18-gage needle is attached to the manometer and then inserted into the vein. To insure successful measurements, the following precautions must be observed:

1 To eliminate the factor of venous spasm incidental to venipuncture, the measurement of the venous pressure should not be made until 8 to 10 min have elapsed after the insertion of the needle.

2. The subject must be relaxed throughout the procedure and this can be repeatedly ascertained by passively flexing the elbow.

3. The arm must not be internally rotated nor excessively abducted to avoid interference with the venous return If a neck vein is employed, excessive rotation of the head must also be avoided for similar reasons

4 The beveled edge of the needle must lie freely within the vein and not impinge against its walls

After the blood rises in the manometer, the tourniquet, or blood-pressure cuff, is released When the column reaches a stationary level, the reading which is recorded presents the *initial venous pressure* by the 'blood-up" method To check the accuracy of this finding, the arm is *then again* compressed with the resultant rise in the blood column in the manometer which confirms the patency of the manometric system When the compression is removed again, the blood flows down again to its previous level or to within 1 to 2 cm above its previous height The level at which the blood in its descent becomes stationary represents the *initial venous pressure* by the "blood-down" method. The presence of respiratory oscillations and the close approximation between the "blood-up" and the "blood-down" procedures are usually indicative of a free manometric system

The *initial venous pressure* having thus been obtained, quantitative determination of the effect of abdominal compression upon the height of the *initial venous pressure* is now made. With this technique, not only is the response to upper abdominal compression quantitatively measured but the Pasteur-Rondot, or "hepatojugular reflux" phenomenon, can be simultaneously recorded by observing the state of fullness of the external jugular veins.

While the needle is still in situ at the level of the recorded initial venous pressure, manual pressure with the outstretched hand is gradually applied to the *right upper abdominal quadrant* for an arbitrary period of one minute, during which the subject breathes regularly and deeply. The rise or fall of the venous pressure above the initial level is recorded. Similar observations are made when the *left lower abdominal quadrant* is compressed The quantitative determination of the effect of compressing the right upper and left lower abdominal quadrants *serves to establish* venous pressure curves characteristic for normal and abnormal circulatory syndromes They consist essentially of the following two components:

1. *The initial* venous pressure as measured in the antecubital or external jugular vein is identical with the venous pressure as recorded by the method of Moritz and von Tabora. The wide fluctuation of the normal range probably bears some relation to the inaccuracy of the zero reference point.

2. The effect of right upper abdominal compression on the fall or rise of the venous column above or below the level which indicates the initial venous pressure determines the presence of either a negative or a positive "hepatojugular reflux" phenomenon, respectively (Table 3-1).

TABLE 3-1 THE EFFECT OF ABDOMINAL COMPRESSION ON VENOUS PRESSURE MEASUREMENTS

Right ventricular function	*Manometric measurement, cm*		*State of fullness (visual) and increased tension (tactile) of external jugular vein (Pasteur-Rondot phenomenon)*	
	During compression of right upper quadrant	*During compression of left lower quadrant*	*During compression of right upper quadrant*	*During compression of left lower quadrant*
Normal	Unchanged or fall of 0 to +2 5	Unchanged or fall of 0 to −2	No change or collapse of vein	No change or collapse of vein
Incipient right heart failure (primary or secondary)	Rise of +1 to +7	Rise of +1 to +6	Increased fullness and tension of vein	Increased fullness and tension of vein
Frank right heart failure (primary or secondary)	Rise of +8 to +20	Rise of +7 to +20	Marked fullness and increased tension of vein	Marked fullness and increased tension of vein

GENESIS OF THE "HEPATOJUGULAR REFLUX" PHENOMENON IN SYSTEMIC VENOUS HYPERTENSION

The "hepatojugular reflux" phenomenon, as it was originally described in congestive failure, is really misnamed, since there is no isolated hepatic component in its genesis. The response is not pathognomonic of congestive failure, since it may also occur in superior caval obstruction (at or below the azygos vein), and in cases of hypervolemia associated with polycythemia vera or with certain adrenal tumors, where it may appear as a transient phenomenon.

Three factors participate in the genesis of the "hepatojugular reflux" phenomenon

Manually Induced Increased Intraabdominal Tension for One Minute. That this is not a "liver" or "diaphragmatic" phenomenon, and simply represents the effect of an increased intraabdominal tension, is confirmed by results when the left lower abdominal quadrant is compressed instead of the right upper quadrant Although the pattern of response is almost identical, the maximum peaks are on a lower level. The one-minute compression period is arbitrary and is employed only for comparative purposes.

Blood Volume and Its Relation to the Vascular Capacity. In hypervolemia, whether due to congestive failure or to other causes, there is a greater splanchnic blood volume than is normally present. Manual compression of the abdomen in such conditions will therefore cause a greater increase in the venous return to the heart. Depending upon the severity of congestive failure, the height of the "hepatojugular reflux" phenomenon will increase only in proportion to the increased venous return but also in relation to the ratio of blood volume to the total venous capacity

The Functional Integrity of the Right Side of the Heart. The functional integrity of the right heart plays the chief role in determining whether the manual increase of intraabdominal tension will elicit a negative "hepatojugular reflux" phenomenon, which is normal, or a positive "hepatojugular reflux" phenomenon, which is abnormal, the latter occurring predominantly in cases of congestive failure, with or without venous hypertension. The significant role attributed to coexisting venous hypertonus, as postulated by Burch, is not borne out by other significant observations which favor mechanical rather than neurogenic factors alone in the genesis of both the venous hypertension and of the "hepatojugular reflux" phenomenon as they occur in congestive heart failure.

It is important to understand the sequence of events that underlies the normal negative "hepatojugular reflux" phenomenon when pressure is exerted on the right upper part of the abdomen The manually increased intraabdominal tension enhances the splanchnic venous return, but the normal right heart, accommodating itself promptly by an increased cardiac output in accordance with Starling's law, maintains a normal pressure in systemic veins of the superior caval system. When the initial "squeezing-out" effect from the splanchnic depots is completed, the venous return from the lower half of the body eventually (within the initial phase of the arbitrary period) becomes diminished, or even momentarily halted, due to the "tourniquet" effect imposed upon the distal inferior vena cava and its tributaries by the increased manually induced intraabdominal tension. Consequently, there is a freer emptying of blood from the upper half of the body through the superior vena cava which, when combined with the diminished venous return from the lower half of the body, leads to a diminished cardiac output This may further contribute to the gradual fall of the initial antecubital or external jugular venous pressure during the latter phase of the one-minute period of abdominal compression

In *congestive failure*, the genesis of the positive "hepatojugular reflux" phenomenon during abdominal compression resides mainly in a malfunctioning right heart combined with an increased splanchnic blood volume. The marked augmentation of the venous return, which exceeds the functional capacity of the heart, creates a bottleneck at the caval openings. Interference with the venous return from the brachiocephalic portion of the body results, and this is consequently reflected in a further rise of the venous pressure within the tributaries of the superior vena cava

The genesis of the positive "hepatojugular reflux" phenomenon in *superior vena caval occlusion* (at or below the azygos vein) is in diametric contrast to the mechanism of this phenomenon in congestive failure. In the latter, the venous return to the heart is increased by this abdominal maneuver, whereas in superior caval occlusion it may actually be decreased.

In the latter, the positive "hepatojugular reflux" phenomenon represents interference with the venous return of blood from the brachiocephalic portion of the body, which then seeks to reach the heart in roundabout fashion via the superficial and deep collaterals that empty into the inferior vena cava. Manual compression of the abdomen temporarily obstructs this venous inflow by exercising a temporary "tourniquet" effect on the collaterals from the superior caval system. A diminished venous return to the heart ensues, which results in a further rise in the antecubital and external jugular venous pressures.

A positive "hepatojugular reflux" phenomenon of transient nature will also occur in *polycythemia vera* or in the presence of certain *adrenocortical tumors associated with hypervolemia*, in this instance atypical venous pressure curves are also obtained. Because of the hypervolemia, abdominal compression yields a *venous return* from the splanchnic region which *is greater than normal*. This increased venous return temporarily overwhelms the normally functioning right heart and is promptly reflected in a *transient increase* of venous pressure in the *tributaries* of the superior vena cava. However, normal right ventricular function eventually overcomes the bottleneck momentarily induced by the increased venous return, as a result of which the venous pressure returns to its previous level before the arbitrary period of one minute ends.

GENESIS OF [illegible] OF [illegible]

Inspiration normally causes an emptying of the brachiocephalic veins with a fall of the venous pressure of about 0.5 cm during its quiet phase while expiration causes a similar rise.[1] Inspiratory filling of the cervical veins has been observed in constrictive pericarditis, in association with a pulsus paradoxus. Although *Wenckebach* originally attributed the inspiratory distention of the cervical veins to adhesions which interfere with inspiratory emptying, the presence of this "paradoxical" sign in syndromes associated with venous hypertension (without mediastinitis) tends to disclaim that the mechanical factor is the sole explanation for its occurrence (Hitzig, 1942). Its presence in *constrictive pericarditis*, in the marked tamponade of *pericardial effusion*, and in *severe congestive heart failure*, where manually induced "hepatojugular reflux" phenomena are universally present, suggests that the inspiratory rise in these "congestive" states during a deep inspiration may simulate (but in a less striking manner) the effect of the abdominal maneuver on the level of the venous pressure in cervical veins. In this way, the venous return, being centrally increased, overloads an inefficient right heart; this overload in turn is reflected in a slight but significant *inspiratory* elevation of the brachiocephalic venous pressure (inspiratory "hepatojugular reflux" phenomenon).

The inspiratory "hepatojugular reflux" phenomenon in *systemic venous hypertension* is not really "paradoxical," for it has a sound physiological basis. Its genesis is based upon alterations of the circulatory but *not* the respiratory dynamics.

Whether or not the cervical veins fill during inspiration is determined largely by the circulatory balance developed between an augmented venous return and the ability of the right heart to handle it. In "congestive" states, the venous return from the liver and portal tributaries is enormously increased, not only because of the greater circulating blood volume present in heart failure, but also because of the disproportionate accumulation of blood in the intraabdominal blood depots, especially in the liver. As a consequence, the insufficient or compressed right heart is overloaded beyond its functional capacity. The *central venous* stasis (stasis of large veins and right atrium) that follows retards the venous influx from the superior vena cava during inspiration and, as a consequence, the inspiratory "hepatojugular reflux" phenomenon makes its phasic appearance.

An inspiratory rise of the cervical venous pressure also occurs *in superior caval occlusion when the obstruction is either at or below the azygos vein*. The mechanism for this pressure *rise in* veins already taut with pressure *parallels the mechanism which* causes elevation of the cervical venous pressure in superior caval occlusion *when the* intraabdominal tension is manually increased. This is also in dia-

[1] A different viewpoint has been presented in Part 2, Chap. 19, and in the first part of this chapter (Moia). *Editor*

GENESIS OF THE "HEPATOJUGULAR REFLUX" PHENOMENON IN SYSTEMIC VENOUS HYPERTENSION

The "hepatojugular reflux" phenomenon, as it was originally described in congestive failure, is really misnamed, since there is no isolated hepatic component in its genesis. The response is not pathognomonic of congestive failure, since it may also occur in superior caval obstruction (at or below the azygos vein), and in cases of hypervolemia associated with polycythemia vera or with certain adrenal tumors, where it may appear as a transient phenomenon.

Three factors participate in the genesis of the "hepatojugular reflux" phenomenon.

Manually Induced Increased Intraabdominal Tension for One Minute. That this is not a "liver" or "diaphragmatic" phenomenon, and simply represents the effect of an increased intraabdominal tension, is confirmed by results when the left lower abdominal quadrant is compressed instead of the right upper quadrant. Although the pattern of response is almost identical, the maximum peaks are on a lower level The one-minute compression period is arbitrary and is employed only for comparative purposes.

Blood Volume and Its Relation to the Vascular Capacity. In hypervolemia, whether due to congestive failure or to other causes, there is a greater splanchnic blood volume than is normally present. Manual compression of the abdomen in such conditions will therefore cause a greater increase in the venous return to the heart. Depending upon the severity of congestive failure, the height of the "hepatojugular reflux" phenomenon will increase only in proportion to the increased venous return but also in relation to the ratio of blood volume to the total venous capacity

The Functional Integrity of the Right Side of the Heart. The functional integrity of the right heart plays the chief role in determining whether the manual increase of intraabdominal tension will elicit a negative "hepatojugular reflux" phenomenon, which is normal, or a positive "hepatojugular reflux" phenomenon, which is abnormal, the latter occurring predominantly in cases of congestive failure, with or without venous hypertension The significant role attributed to coexisting venous hypertonus, as postulated by Burch, is not borne out by other significant observations which favor mechanical rather than neurogenic factors alone in the genesis of both the venous hypertension and of the "hepatojugular reflux" phenomenon as they occur in congestive heart failure.

It is important to understand the sequence of events that underlies the normal negative "hepatojugular reflux" phenomenon when pressure is exerted on the right upper part of the abdomen The manually increased intraabdominal tension enhances the splanchnic venous return, but the normal right heart, accommodating itself promptly by an increased cardiac output in accordance with Starling's law, maintains a normal pressure in systemic veins of the superior caval system When the initial "squeezing-out" effect from the splanchnic depots is completed, the venous return from the lower half of the body eventually (within the initial phase of the arbitrary period) becomes diminished, or even momentarily halted, due to the "tourniquet" effect imposed upon the distal inferior vena cava and its tributaries by the increased manually induced intraabdominal tension Consequently, there is a freer emptying of blood from the upper half of the body through the superior vena cava which, when combined with the diminished venous return from the lower half of the body, leads to a diminished cardiac output This may further contribute to the gradual fall of the initial antecubital or external jugular venous pressure during the latter phase of the one-minute period of abdominal compression

In *congestive failure*, the genesis of the positive "hepatojugular reflux" phenomenon during abdominal compression resides mainly in a malfunctioning right heart combined with an increased splanchnic blood volume. The marked augmentation of the venous return, which exceeds the functional capacity of the heart, creates a bottleneck at the caval openings Interference with the venous return from the brachiocephalic portion of the body results, and this is consequently reflected in a further rise of the venous pressure within the tributaries of the superior vena cava

The genesis of the positive "hepatojugular reflux" phenomenon in *superior vena caval occlusion* (at or below the azygos vein) is in diametric contrast to the mechanism of this phenomenon in congestive failure In the latter, the venous return to the heart is increased by this abdominal maneuver, whereas in superior caval occlusion it may actually be decreased.

In the latter, the positive "hepatojugular reflux" phenomenon represents interference with the venous return of blood from the brachiocephalic portion of the body, which then seeks to reach the heart in roundabout fashion via the superficial and deep collaterals that empty into the inferior vena cava. Manual compression of the abdomen temporarily obstructs this venous inflow by exercising a temporary "tourniquet" effect on the collaterals from the superior caval system. A diminished venous return to the heart ensues, which results in a further rise in the antecubital and external jugular venous pressures.

A positive "hepatojugular reflux" phenomenon of transient nature will also occur in *polycythemia vera* or in the presence of certain *adrenocortical tumors associated with hypervolemia*, in this instance atypical venous pressure curves are also obtained. Because of the hypervolemia, abdominal compression yields a venous return from the splanchnic region which is greater than normal. This increased venous return temporarily overwhelms the normally functioning right heart and is promptly reflected in a transient increase of venous pressure in the tributaries of the superior vena cava. However, normal right ventricular function eventually overcomes the bottleneck momentarily induced by the increased venous return, as a result of which the venous pressure returns to its previous level before the arbitrary period of one minute ends.

GENESIS OF INSPIRATORY FILLING OF THE CERVICAL VEINS (INSPIRATORY HEPATOJUGULAR REFLUX)

Inspiration normally causes an emptying of the brachiocephalic veins with a fall of the venous pressure of about 0.5 cm during its quiet phase while expiration causes a similar rise.[1] Inspiratory filling of the cervical veins has been observed in *constrictive pericarditis*, in association with a pulsus paradoxus. Although Wenckebach originally attributed the inspiratory distention of the cervical veins to adhesions which interfere with inspiratory emptying, the presence of this "paradoxical" sign in syndromes associated with venous hypertension (without mediastinitis) tends to disclaim that the mechanical factor is the sole explanation for its occurrence (Hitzig, 1942). Its presence in *constrictive pericarditis*, in the marked tamponade of *pericardial effusion*, and in *severe congestive heart failure*, where manually induced "hepatojugular reflux" phenomena are universally present, suggests that the inspiratory rise in these "congestive" states during a deep inspiration may simulate (but in a less striking manner) the effect of the abdominal maneuver on the level of the venous pressure in cervical veins. In this way, the venous return, being centrally increased, *overloads* an inefficient right heart; this overload in turn is reflected in a slight but significant inspiratory elevation of the brachiocephalic venous pressure (inspiratory "hepatojugular reflux" phenomenon).

The inspiratory "hepatojugular reflux" phenomenon in *systemic venous hypertension* is not really "paradoxical," for it has a sound physiological basis. Its genesis is based upon alterations of the circulatory but *not* the respiratory dynamics.

Whether or not the cervical veins fill during inspiration is determined largely by the circulatory balance developed between an augmented venous return and the ability of the right heart to handle it. In "congestive" states, the venous return from the liver and portal tributaries is enormously increased, not only because of the greater circulating blood volume present in heart failure, but also because of the disproportionate accumulation of blood in the intraabdominal blood depots, especially in the liver. As a consequence, the insufficient or compressed right heart is overloaded beyond its functional capacity. The central venous stasis (stasis of large veins and right atrium) that follows retards the venous influx from the superior vena cava during inspiration and, as a consequence, the inspiratory "hepatojugular reflux" phenomenon makes its phasic appearance.

An inspiratory rise of the cervical venous pressure also occurs in *superior caval occlusion* when the obstruction is either *at or below the azygos vein*. The mechanism for this pressure rise in veins already taut with pressure parallels the mechanism which causes elevation of the cervical venous pressure in superior caval occlusion when the intraabdominal tension is manually increased. This is also in dia-

[1] A different viewpoint has been presented in Part 2, Chap. 19, and in the first part of this chapter (Moia). Editor

metric contrast to the mechanism which causes the inspiratory rise of venous pressure in right heart failure, where the rise is due to central venous stasis or to an overloading of the right heart by an increased venous return. In *superior caval occlusion*, there is no central stasis; the inspiratory venous return to the heart is actually diminished. The increased filling of the veins of the neck therefore results from the increased intraabdominal tension during inspiration which retards the flow of blood through the circuitous abdominal channels to the inferior caval pathway by means of which blood is transported to the heart from the upper part of the body

THE RESPONSE OF THE INITIAL VENOUS PRESSURE LEVEL TO ABDOMINAL COMPRESSION (CHARACTERISTIC DYNAMIC VENOUS PRESSURE CURVES) (TABLE 3-2)

Dynamic Venous Pressures (or Curves) of Normal Right Ventricular Function. In those individuals with an unimpaired circulatory system, the initial venous pressure level either remains unchanged or falls (from 0 to −2 5 cm) during one minute of compression of the right upper abdominal quadrant. The venous pressure curves in normal children are identical with those obtained in normal adults

In cases of *hypervolemia*, there is a parabolic rise in the venous pressure level during the period of abdominal compression which gradually falls to the base line before the arbitrary period of abdominal compression ends.

Dynamic Venous Pressures (or Curves) of Impaired Circulatory Function. In patients with *isolated left heart failure* without gross evidence of coexisting right ventricular dysfunction, compression of the right upper part of the abdomen will yield similar results to those obtained in normal individuals, namely, no change or a fall in the height of the venous column

In cases of *left heart failure with coexisting incipient right ventricular fatigue* secondary to pulmonary venous engorgement and pulmonary arterial hypertension, the rise on compression of the right upper abdominal quadrant may

TABLE 3-2 DYNAMIC VENOUS PRESSURE MEASUREMENTS IN VARIOUS CIRCULATORY SYNDROMES

Circulatory syndrome	*Manometric measurements, cm*			
	Initial pressure (antecubital or external jugular)	*During abdominal compression (effect of increased intraabdominal tension), rise or fall*		*Femoral pressure*
		Right upper quadrant	*Left lower quadrant*	
Normal	4-8 (range 2-10)	Unchanged or fall 0 to −2 5	Unchanged or fall; 0 to −1 5	4-10
Left heart failure	6-10	No change or slight fall 0 to −1 5	No change or slight fall 0 to −1 5	6-10
Left heart failure with incipient right heart failure	6-10	Rise +1 to +7	Rise +1 to +6	6-10
Incipient right heart failure (primary)	6-10	Rise +1 to +7	Rise +1 to +6	6-10
Frank right heart failure (primary and secondary)	11-30	Rise +8 to +20	Rise +7 to +20	11-30
Frank right heart failure (dehydration with lowered ratio between reduced circulating blood volume and distended venous capacity)	8-10	Rise +6 to +15	Rise +6 to +12	8-10
Constrictive pericarditis	20-35	Rise, +15 to +25	Rise +15 to +25	20-35
Pericardial effusion with tamponade)	15-30	Rise +10 to +20	Rise +10 to +20	15-30
Superior vena caval obstruction (above azygos vein)	12-15	Most probably fall or, rarely, slight rise +1 to +3	Most probably fall	4-10
Superior vena caval obstruction (below azygos vein)	20-30	Rise +6 to +18	Rise: +4 to +10	4-10

range from 1 or 2 cm to levels as high as 8 to 10 cm Similar values may be observed in cases of *incipient right heart failure* secondary to intrinsic disease of the lungs (such as lymphangitic carcinomatosis of the lungs or pulmonary sarcoidosis).

In *frank right heart failure*, in *constrictive pericarditis*, in pericardial effusion with cardiac tamponade, or in the *paroxysmal arrhythmias*, the rise in the venous column on abdominal compression will depend upon the degree of right ventricular fatigue, as is observed in cases of *hyposystolic failure*, or upon interference with diastolic relaxation and filling, as seen in cases of *hypodiastolic failure*. In such conditions, the venous pressure will, on compression of the right upper abdominal quadrant, rise from 10 to 20 cm above the initial venous pressure level A positive "hepatojugular reflux" phenomenon as high as 25 cm has also been observed manometrically in a case of constrictive pericarditis.

In cases of *chronic bronchopulmonary disease*, whenever there is an associated *increased* intrapleural pressure and an increased resistance to venous inflow (as occasionally occurs in conditions of obstructive *emphysema* and bronchial asthma), right heart failure may supervene (decompensated *cor pulmonale*) and an abnormal venous pressure curve may appear.

CLINICAL VALUE OF DYNAMIC VENOUS PRESSURE CURVES

Dynamic venous pressure curves have greater clinical applicability than simple "static" measurements for reasons other than the fact that the latter show frequent overlapping in normal individuals, in compensated, and in occasional decompensated cardiac patients. The characteristic venous pressure response to an intrinsic increment in venous return through the mechanism of abdominal compression provides valuable aid in the differentiation of extracardiac from true cardiac conditions If properly employed, both the clinical Pasteur-Rondot phenomenon and its manometric equivalent can permit prompt bedside evaluation of borderline cardiac cases where the mimicry is confusing or where the initial venous pressure, due to local causes, may be high normal or even above normal.

The quantitative or manometric reading of venous pressure curves is, however, superior to visual or tactile inspection of the neck veins before and during the Pasteur-Rondot maneuver, because cervical veins not infrequently present anatomic aberrations. This is sometimes revealed in patients whose external jugular veins are congenitally absent, malformed, hidden behind a thickened panniculus; or whose veins are unduly prominent or gaping as a result of long-standing bronchopulmonary disease, phlebosclerosis, or other degenerative changes.

Venous pressure curves are also of inestimable value in the diagnosis of *constrictive pericarditis*. A normal radiographic cardiac silhouette in the presence of a high initial and a markedly abnormal venous pressure response to compression of the upper part of the abdomen (positive "hepatojugular reflux" phenomenon), should lead immediately to the suspicion of this diagnosis as well as to the feasibility of eventual pericardiectomy. This dictum holds if the abnormal response to abdominal compression persists even if the initial venous pressure should fall sufficiently to lie in the normal range, since this happens occasionally following the removal of massive ascites or vigorous dehydration. However, if, before or perchance after vigorous therapy a normal venous pressure curve with a negative "hepatojugular reflux" phenomenon appears, the diagnosis of constrictive *pericarditis* can be safely discarded.

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no

A more favorable prognosis in cases of heart failure may be made if progressive reduction in the measured height of the "hepatojugular reflux" phenomenon takes place under a therapeutic regimen The prognosis is even more hopeful when, under therapy, there is an actual reduction in the height of the initial venous pressure and simultaneously a drop be-

phenomenon). Conversely, a persistently abnormal venous pressure curve, as revealed in an unyielding positive Pasteur-Rondot phenomenon despite all therapeutic measures, compels a poor prognosis. However, this does not apply to constrictive pericarditis. Although the abnormal venous pressure curve

pattern in this disease also fails to yield during extensive medical therapy, its behavior following adequate surgical release of the incarcerated ventricles is dramatically altered.

An abnormal venous pressure curve, or even the presence of a mildly positive "hepatojugular reflux" phenomenon in cases of congestive heart failure, serves as an indication, depending on the urgency of the symptoms, for the gradual or prompt removal of excessive extracellular fluid (plasma and interstitial fluid) The subsequent need for periodic or repetitive diuretic therapy may be confirmed by employing the reappearance of the positive "hepatojugular reflux" phenomenon as the signal for the reduction of excess body water.

The prompt reduction in the circulating blood volume via *phlebotomy* may be a lifesaving procedure in the presence of pulmonary venous engorgement when all other therapeutic measures have momentarily failed. To relieve the symptoms of such a cardiac emergency, even the mere removal of 300 ml of blood from the veins of a patient with left-sided congestive heart failure may be dramatically effective, especially in cases where the "arm-to-tongue" circulation time is unduly prolonged and the venous pressure curve, during abdominal compression, reveals a disproportionate rise above its initial level

Although *venesection* causes a lowering of the systemic venous pressure with an appreciable fall in the venous return in both normal subjects and in cardiac patients, its most dramatic effect occurs when there is an imbalance in the failure of the two ventricles (left greater than right). The symptoms of pulmonary engorgement and edema in acute left ventricular failure, regardless of the coexistence of an abnormal venous pressure curve indicative of incipient or frank right heart failure are usually ameliorated by immediate action directed towards establishing a lessened venous return Bloodless phlebotomy via the application of *tourniquets* to the extremities may suffice, but venesection is often a necessity if the hemoglobin content of the blood is adequate. Should venesection in the presence of an equivocal hemoglobin level lead to undue lowering of the venous pressure and venous return, the blood, if collected aseptically, may be returned to the patient either whole or after its plasma has been removed (packed cells).

The prompt therapeutic effects of phlebotomy are less apparent in those cases of congestive heart failure where a characteristic venous pressure curve of frank right heart failure is obtained. Although removal of 300 to 500 ml of blood may lower both peaks of the venous pressure curve, i.e., the height of the initial venous pressure and its response to abdominal compression, the acute symptoms attributable to dominant pulmonary engorgement are less affected than they are in those patients who still retain efficiency of the right ventricle. That this is a function related to the maintained efficiency of the right heart is borne out by clinical observations in left-sided heart failure where acute symptoms of pulmonary congestion often lessen considerably or almost disappear when failure of the right heart supervenes There are, however, instances of dominant left-sided failure where phlebotomy, despite the presence of coexisting frank right heart failure, does exert a prompt salutary effect. Apparently, venesection, by lessening the inflow of blood to the lungs, also influences pulmonary edema through a variety of mechanisms, among which is the reduction of the increased lymphatic pressure (lymphatic hypertension secondary to systemic venous hypertension of right heart failure). The lessening of the pulmonary edema may be partially attributed to altered lymphatic function which improves sufficiently, when the peripheral venous pressure is acutely lowered, to favor resorption of the alveolar fluid of pulmonary edema

7

Inspection, palpation, and low-frequency tracings

Inspection and Palpation
PEDRO COSSIO

Clinical Evaluation of Pulsations of the Chest Wall
WILLIAM DRESSLER

The Kinetocardiogram—Ultra Low-frequency Precordial Movements
F. E. EDDLEMAN, JR.

The Accelerogram of the Precordium
LESLIE M. ROSA

INSPECTION AND PALPATION

Inspection and palpation of the heart should be performed simultaneously because these two methods complement each other. This examination should include the whole chest, with special attention to the precordial region, the neck, the epigastrium and, if necessary, the lateral walls of the chest and the back. *Inspection* should be performed by viewing the patient directly and symmetrically for the purpose of comparison, as well as tangentially in order to appreciate the movements of the chest. *Palpation* should be performed first with the whole hand, placing it, either softly or with gentle pressure, over the chest, first holding it still, then moving it about, and finally using gentle digital pressure in order to feel with greater precision the various pulsations. The patient is examined first *during normal respiration*, and then in *expiratory apnea*, although at times it is necessary to observe him *during deep breathing* and also in *inspiratory apnea*. This is one of the most important methods of physical examination, which deserves more attention than it ordinarily receives. By means of inspection and palpation, one can recognize the following signs: deformities, jugular engorgement, pulsations, hyperesthesia, point of maximum impulse, and thrills.

Deformities. Deformities may be either *diffuse* or *localized depressions* or *bulgings* of the precordial region or any other part of the thorax, neck, and abdomen. A *diffuse depression* of the precordial region is generally part of a retraction of the left hemithorax due to extracardiac causes, usually scoliosis. A *localized depression* of any part of the precordial region is likewise of extracardiac origin, for example, a thoracotomy scar or a congenital or acquired depression of the lower third of the sternum (*scaphoid* or *shoemaker's chest*). A *diffuse bulging* may be part of the bulging of the left chest from extracardiac causes, particularly scoliosis, but is sometimes due to *severe cardiac enlargement* or to an *abundant pericardial effusion* in an elastic thorax, such as [illegible]

be due to parietal lesions (osteochondritis, osteosarcoma, abscess) or is of cardiovascular origin. In the latter case, a localized bulging

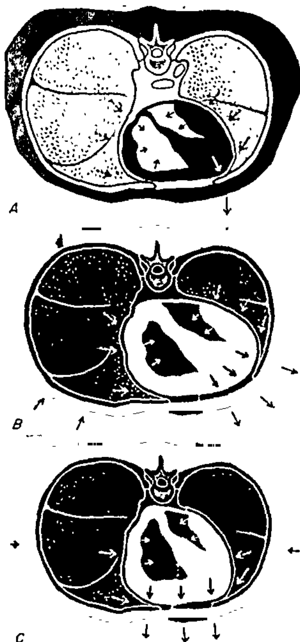


Fig. 3-9. A Scheme of the origin of the normal apical thrust B Scheme of the diffuse precordial thrust caused by an enlarged left ventricle (lateral thrust) C. Scheme of the diffuse precordial thrust caused by an enlarged right ventricle (sagittal thrust).

near the nipple may be caused by a *parietal aneurysm of the heart,* bulging in the 3d left interspace, by an enlargement of the conus of the right ventricle or, more rarely, by an *aneurysm of the pulmonary artery,* and a bulging in the 2d right interspace, by an *aneurysm of the ascending aorta.* A criterion by which one may differentiate between bulges of cardiovascular and those of extracardiac origin is that the former are more commonly animated by visible or palpable pulsations, although it should be remembered that collar-button abscesses may exist in the chest wall, and that they may have similar pulsations, which are not expansive (transmitted pulsations).

Jugular Engorgement. Normally, when the patient is supine and his head lies on one or two pillows, the external jugular veins are not visible, since they are collapsed, except in the lower third of the neck where they may be somewhat prominent and sometimes pulsating (venous pulsations; see below). The jugular veins, when they are engorged in this position and can be observed along the whole length of the neck, indicate an increase in the intrathoracic pressure, if the engorgement is apparent in the semirecumbent or standing position, *high pressure* is present. The veins are engorged during an attack of bronchial asthma, but then they collapse during inspiration; if this collapse does not occur, there is venous hypertension due to either obstruction of the superior vena cava, or heart failure. Venous pulsations are absent in the former but present in the latter Furthermore, in cases of heart failure, the engorgement may be increased by manual pressure over the abdomen, especially over the right upper quadrant (*abdominojugular,* or *hepatojugular reflux*).

External jugular veins, which are not only engorged but also *tortuous,* signify *long-standing venous hypertension,* i.e , a chronic condition It may be that *only the left* external jugular is engorged, this indicates an elongation and dilatation of the aortic arch due to arterial hypertension, arteriosclerosis, or syphilitic aortitis, with consequent compression of the left innominate venous trunk (*sign of Gonzales-Sabathié*)

Pulsations. Pulsations are movements of propulsion (positive pulsations) or of depression (negative pulsations) due either directly or indirectly to ventricular systole, and can be divided into thoracic pulsations, cervical pulsations, and epigastric pulsations according to their positions.

THORACIC PULSATIONS Thoracic pulsations are frequently encountered They may be *localized* in one or two intercostal spaces, and *pressure with the finger tips* should be applied in order to perceive them more accurately, they may be *diffuse,* due to displacement of the ribs and sternum, with compensatory shifts

which preserve the original *volume* of the chest Its walls are elastic, and if one diameter *is increased, another* is proportionately reduced (*Fig* 3-9).

In ordinary conditions of rest or enforced expiratory apnea, the chest of an adult, and especially that of an elderly person, does not present on its surface any pulsation, in spite of the constant changes *in volume* of the heart and the *corresponding expulsion* of blood toward the *periphery*. This is possible because of expansion of the pulmonary segments with the shift of air from one to another (*cardiopneumatic movements*, Part 4, Chap. 9, Tracings of Pressure and Speed of Respiration) and to the inflow of blood by way of the venae cavae *On the other hand*, in children and adolescents, whose chest walls are more elastic, *and in adults* with cardiac hyperactivity (*neurocirculatory* asthenia, emotion, or exertion), inspection of the precordium including [illegible] matic movements nor the return of blood by way of the veins is sufficient to compensate for the decreased volume of the heart during ejection. If, instead of observing the chest tangentially, one places his hand with a certain pressure a little to *the left of the sternum*, between the 2d and 4th *interspaces, with the patient in forced expiratory* apnea, the above-mentioned *negative* pulsation is usually transformed into a positive one, particularly in flat chests. This is due to depression of the rib cage by manual pressure and its movement during the systolic increase of the anteroposterior diameter of the ventricles.

In pathological *conditions, several* localized *pulsations may appear, or there may* be an increase of the normal pulsations, as well as generalized or diffuse pulsations of great diagnostic value.

The *positive localized pulsations* may be due to: (1) systolic expansion of a *parietal aneurysm of the heart*; in this condition the pulsation will appear in the 3d or 4th *left* interspace medial *to the point* of maximum *impulse*;

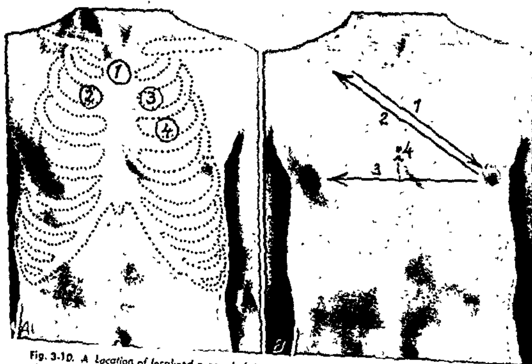


Fig. 3-10. *A Location of localized precordial thrusts* 1, *Aneurysm* of the aortic arch. 2, Dilatation of the ascending *aorta* 3, *Dilatation of the* pulmonary artery. 4, *Ventricular* aneurysm B Direc[illegible]tion of diffuse pulsations *of the* chest. 1, Due to *enlargement of the left* ventricle [illegible] lateral thrust caused by aneurysm of the [illegible] tricuspid *Insufficiency* or mitral insufficiency [illegible] due to right ventricular *enlargement.*

(2) expansion of *an aneurysm* or *dilatation of the pulmonary artery,* which produces a pulsation in the 2d interspace, a little to the left of the sternum, (3) *dilatation* or *aneurysm of the ascending aorta,* which can be found a little to the right of the sternum in the 2d interspace; or (4) expansion of *an aneurysm of the descending aorta,* which gives rise to a pulsation in the left interscapulovertebral region (Fig. 3-10).

Localized negative pulsations, also called uni- or pluricostal retractions according to whether they involve one or two intercostal spaces, may be of the precordial region (*Jaccoud's sign*) or below the left scapula (*Broadbent's sign*). These are due to traction of pleural or pericardial adhesions by a powerful systole. However, in a very elastic chest, like that of a child, an unusually strong systole may produce them This happens typically in aortic insufficiency

Diffuse pulsations are more complex movements, often of a shifting or rocking type There are five having a definite diagnostic significance·

1. *Sagittal negative pulsation* is an extensive and sudden systolic depression of the precordial region in the anteroposterior plane In the child, whose chest is small and elastic, there may also be a multicostal retraction This sign is actually only an exaggeration of what may occur under normal conditions It is appreciated better by inspection since palpation usually *makes it positive, and it is due to an* exaggerated systolic contraction causing greater systolic ejection It can be observed in cases of hyperthyroidism, anemia, and severe aortic insufficiency.

2. *Sagittal positive pulsation* is an extensive systolic thrust of the precordial region in a posteroanterior plane, particularly noticeable in the peristernal area at the level of the 3d left interspace; it is best appreciated with the heel of the hand placed firmly (*Dressler's maneuver*). It is due to an enlargement of the right ventricle and occurs in cases of mitral stenosis, congenital heart disease, and, less often, chronic cor pulmonale.

3 *Oblique pulsation* is a systolic thrust of the precordial region on the left side, while there is depression and traction of the right chest, it is a truly *rocking movement* which follows the longitudinal axis of the heart. It is due to the pinning of the heart between the vertebral column and the anterior chest wall because of severe enlargement of the left ventricle, and it is found in arterial hypertension and in aortic valvular lesions. However, *a retrocardiac tumor or aneurysm can produce it.* In the latter instance, the ventricular systolic thrust is followed by a second thrust caused by expansion of the aneurysm (*double impulse of Hope*).

4. *Inverted oblique pulsation* is a systolic rocking motion in a direction opposite to the one described above As the precordial region is depressed, the upper part of the right chest is elevated. This occurs in aneurysms of the ascending aorta and is due to the expansion of the aneurysmal sac.

5 *Transverse pulsation* is also a type of rocking systolic movement whereby the precordial region is depressed and the right chest elevated on a transverse axis, i.e., across the base of the chest This is due to the passage of blood from the left to the right hemithorax during cardiac systole, as occurs in tricuspid insufficiency with venous regurgitation toward the liver, or in mitral insufficiency concomitant with a large left atrium which is largely situated in the right hemithorax

CERVICAL PULSATIONS. Normally, and above all in young individuals, the neck presents two types of pulsation, one of *venous origin,* which is seen better than it is palpated (venous pulse), and another of *arterial origin,* which can be palpated more easily *than it can be* observed (arterial pulse)

The *venous pulse* is due to the variations in the volume of the veins of the neck caused by the greater or lesser filling which is dependent upon the oscillations of right atrial pressure during the cardiac cycle It is represented on a tracing by a presystolic wave (the atrial A wave), followed by a small notch (C wave), then by a depression which coincides with the ventricular systole (systolic collapse) and, finally, by a positive wave (V wave). This is seen at the base of the neck, over the lower third of the sternocleidomastoid muscle, and in the jugular fossa, in which instance it is due to the external jugular vein, or it may be observed in the supraclavicular fossa, where it is due to the external jugular as well as the subclavian vein In order to observe this, the subject must be supine with the head only slightly raised, if the head is elevated at too

great an angle, the pulsation moves towards the base of the neck until it completely disappears.

The *arterial pulsation* is due to the transmission of the pressure wave originating in the left ventricle. It is a single systolic wave (positive pulsation) which can be palpated more easily than it can be seen since it is caused by a pressure difference rather than a change of volume It is felt along both carotid arteries and is well perceived if the fingers are placed between the larynx and the anterior border of the sternocleidomastoid muscle. In obese individuals, the index finger placed in the suprasternal fossa may feel the arterial pulsations produced by the aortic arch and its branches. This can be done with the patient in a supine position and in expiratory apnea, since the elevation of the diaphragm pushes the heart and the great vessels upwards

In pathological conditions, these normal venous and arterial pulsations may present modifications of diagnostic value, the former is particularly valuable in the clinical recognition of arrhythmias and of tricuspid insufficiency, the latter in the diagnosis of aortic insufficiency and diseases of the arterial system Unfortunately, it is at times difficult to differentiate between these two types of pulsation, so that one should rely on graphic tracings

The most significant pathological modifications of the venous pulse are the following

1 The *positive venous pulse*, also called the ventricular venous pulse, is the most important It consists of a visible and somewhat palpable pulsating systolic wave which occurs instead of the systolic collapse of the normal venous pulse. It is preceded at times by the normal presystolic wave, in this case there is an undulation of a frequency which is just double the cardiac rate (*undulant venous pulse*) It is caused by the reflux of blood toward the veins of the neck during ventricular systole when there is either tricuspid insufficiency or mitral insufficiency plus an atrial septal defect, or when there are simultaneous ventricular and atrial contractions This may be constant (nodal rhythm) or occasional (complete AV block, ventricular tachycardia, nodal premature contractions) The recognition of this pulsation is simple when it occurs in the external jugular or other superficial veins, however, if it occurs in the deep veins (particularly the internal jugular), its differentiation from the carotid pulse is difficult and may be impossible Data which speak in favor of a positive *venous* pulsation are: change of location and even disappearance with changes of position of the body and, above all, the coexistence of a positive hepatic pulse and a weak radial pulse.

2. The *stasis venous pulse* is observed in patients having engorged jugular veins; there is a slight depression which follows the arterial pulse (*diastolic collapse*). This is found in heart failure with atrial fibrillation and is due to permanent engorgement of the venous system with partial emptying in the period of rapid filling.

3. The *high venous pulse* is observed along the entire neck, even as high as the angle of the mandible lifting the ear lobe, it is usually more marked with the patient in dorsal decubitus but sometimes occurs only in a standing position It is related to the degree of stasis of the venous system due to heart failure.

4 The *pathologic presystolic venous pulse* is an exaggeration of the normal presystolic wave, and is due to an increased force of right atrial contraction (tricuspid stenosis, cor pulmonale, heart failure with sinus rhythm) It is differentiated from the normal pulse by the facts that it is palpable, there is engorgement of the external jugular veins, and there are presystolic hepatic pulsations

5 In *venous flutter* the external jugular veins present a series of small rapid beats at a rate of 200 or more per minute connected with a disturbance of rhythm (*atrial flutter*)

The most significant pathologic alterations of the arterial pulse of the neck are the following·

1 *Arterial dance* is a change in which the arterial pulse is not only palpable but also visible, and is observed both along the carotid arteries and in the supraclavicular and suprasternal regions It is produced by an increase in pulse pressure and is typical of aortic insufficiency, although it also occurs in hyperthyroidism, hypertension (especially in coarctation of the aorta), arteriovenous fistula, and anemia

2. The *suprasternal pulse* is a localized, palpable, and visible pulsation of the suprasternal fossa, which may be observed with the

patient in any position and even in deep inspiration. When marked, it is produced by dilatation and elongation of the aortic arch due to hypertension, atherosclerosis, or syphilitic aortitis It may also be caused by elongation and flexion of the innominate artery, due to either congenital anomaly or arteriosclerosis

3. The *supraclavicular pulse* is a pulsation situated in one or both supraclavicular fossas, more frequently the right, and generally it is only palpable. It originates in dilatation and elongation of the aortic arch due to hypertension, arteriosclerosis, or syphilis, as well as to similar lesions of the subclavian arteries which are due to hypertension and arteriosclerosis.

EPIGASTRIC PULSATIONS By epigastric pulsations are meant the motions of depression (negative pulsation) or thrust (positive pulsation) located in this region and produced by cardiac, aortic, or hepatic pulsations.

Normally, if an individual, particularly a lean one with a flat abdomen, is in dorsal decubitus, and *especially if he is also in inspiratory apnea*, his epigastrium (principally its upper region) presents a slight *systolic retraction* which does not disappear even if the hand is placed over the abdomen This retraction is due to the sudden decrease in intra-abdominal pressure caused by the elevation of the diaphragm during ventricular systole It is observed more clearly when there is cardiac hyperactivity, like that which accompanies strong emotion, effort, or fever Also, in normal individuals in *dorsal decubitus* (more so in expiratory apnea and only in very thin individuals), the epigastrium may likewise present a *positive pulsation*, which is lower and more toward the left of the midline than the negative pulsation It is produced by the *systolic expansion of the abdominal aorta*, and it is appreciated more clearly if the abdomen is depressed by the examiner's hand In other words, in normal individuals, the epigastrium may present a negative pulsation of cardiac origin (inspection) as well as a positive pulsation of aortic origin (inspection, palpation), the latter is more marked in expiratory apnea since deep inspiration will make it disappear (Cossio).

In cases of *cardiac enlargement*, particularly of the right ventricle, and more so if the diaphragm and heart are descended (bronchial asthma; pulmonary emphysema with chronic cor pulmonale), the epigastric pulse is negative but becomes positive when the fingers are pressed inward and slightly upward in the costal angle, or slightly to the left of the xiphoid process, especially in deep inspiration. Moreover, in cases of elongation and dilatation of the abdominal aorta, with or without aneurysm, the positive (aortic) epigastric pulse is seen even in individuals who are not especially slender, and the hand can palpate perfectly well a cylindrical, fusiform, or saccular formation and its expansive pulsation. Finally, the whole epigastrium may present a *positive diffuse pulsation* whenever there is a pulsation of the liver due to tricuspid insufficiency, mitral insufficiency with atrial shunt, cor pulmonale, or cardiac tamponade. In this case, there will always be a large, pulsating liver and a visible, positive venous pulse in the neck.

Hyperesthesia. The sensitivity of the chest, including the precordial region, does not differ from that of other regions, except that pressure over the breast in the female produces pain. When touching, pinching, scraping, or pulling the hairs of the chest produces discomfort or pain, there is superficial hyperesthesia. If the stimulus is represented by moderate pressure, there exists a deep hyperesthesia.

Superficial hyperesthesia occurs in cases of psychoneurosis, folliculitis, dermatitis, diseases of the nerve roots (particularly herpes zoster), and in exceptional cases of coronary insufficiency, myocardial infarct, or paroxysmal precordial pain of coronary type In the latter instances, the hyperesthesia may extend to the cubital quarter of the left upper extremity.

Deep hyperesthesia occurs in lesions of the chest wall (especially costal osteochondritis) or of the pectoral muscle (chronic coronary insufficiency). In the case of pectoral muscle involvement, it is most marked over the infraclavicular costal insertions (trigger zone).

Apical Thrust. The apical thrust, or *point of maximum impulse*, is a systolic propulsion, a true positive pulsation, at times accompanied by a brief *thrill and a sensation of thrust*. It is related to the apex of the heart, although it does not coincide exactly with the latter's frontal projection on the chest wall, but is somewhat external and superior to it. The pulsation is due to *pressure of the apex of the*

heart against the chest wall during its systolic hardening plus its rotation to the right, a brief change in position which is produced only in the first part of systole. Later on, there is a progressive reduction of cardiac volume due to ejection.

The "thrill" or "thrust" is nothing more than *the vibration of the 1st heart sound transmitted* through the contact of the apex with the chest wall.

Normally, the apical thrust is limited to the 4th *intercostal space* inside the midclavicular *line and includes an area of* one or two fingerbreadths However, in slender individuals, in standing position or in deep inspiration, the apical thrust is found in the 5th interspace *It is more* marked during expiration and in left lateral decubitus, in the latter position, it is displaced laterally to beyond the midclavicular line

As a rule, it is present in the child and adolescent, chiefly in left lateral decubitus On the other hand, it is often absent *in the adult* with a well-developed, muscular, *or obese* chest, and is exceptional in elderly individuals Such differences are due to the degree of cardiac activity, greater *in infancy* and adolescence than in senility, and to the ratio between the volume of the heart and that of the chest, smaller in the former and greater in the latter The point of maximum impulse may have modifications of location, mobility, and form, which are of diagnostic value

A displacement of the point of maximum impulse can be upwards, downwards, or towards one side It may be due to extrinsic causes, like pushing or pulling of the heart, or to intrinsic causes, where the heart itself is altered in size, form, or position

Extrinsic displacements upward, to the 3d and even the 2d intercostal space, are due to *great elevation of the left diaphragm* because of paralysis or increase of abdominal pressure (pregnancy, meteorism, ascites). Its descent to the 5th or *even the 6th* interspace is due to *cardioptosis*, which is only part of a diffuse lowering of the viscera Its displacement to the left of the *midclavicular* line is produced by *retraction* of the left hemithorax (atelectasis, pulmonary or pleural fibrosis) or to *distention* of the *right* hemithorax (pleural effusion, tumors). Sometimes, a displacement toward the right, even to the degree of passing beyond the sternum (*acquired dextrocardia*), is due to *the same retractile or expansive processes*, but acting in the opposite direction.

The *intrinsic displacements* are: (1) small, upwards, due to pericardial effusion where the accumulation of fluid is on the lower part; (2) toward the right, passing beyond the sternum, due to congenital dextrocardia or situs inversus, (3) toward the left and downward because of ventricular enlargement (the magnitude of the displacement is in direct proportion to the degree of enlargement); in this instance, the lateral *displacement predominates* in enlargement of the left ventricle and the downward displacement in enlargement of the right. This is explained by the directions in which these ventricular enlargements occur and the *repercussions* that *they* have on the *position* of the heart: there is a horizontal and counterclockwise rotation in enlargement *of* the left ventricle, and a vertical and clockwise rotation in enlargement of the right

A lack of mobility or *fixation of the point of maximum impulse*, in spite of changing the position of the subject from dorsal to lateral decubitus (particularly left lateral decubitus), and deep respiration, is due to external pericardial adhesions, which are resistant to stretch (*Friedreich's sign*).

The *modifications* of form or character of the apical thrust are the following:

1 *Tremulation*. If, instead of one pulsation, there are two, one systolic and the other diastolic, *there is* a tremulation of the entire precordial region *which is* the tactile representation of a [illegible]

ha [illegible] followed by a pulsation, there is first a small propulsion and then a vibration This occurs chiefly in mitral *stenosis*, but also in atrial fibrillation, and is due to retardation and accentuation of the 1st sound which occurs under the above-mentioned conditions (*Cossio's sign*).

3 *Prominent apical thrust* This type of thrust (called *choc en dôme*), occurs when, instead of a brief pulsation limited to one intercostal space, there is a prominent and extensive thrust which lifts the hand as if the latter were covering a billiard ball; most important of all, the thrust is persistent and oc-

cupies the entire systole (*Bard's sign*). It is produced by a cardiac enlargement due to dilatation or hypertrophy. It is typical of aortic insufficiency or, less often, of patients with a parietal aneurysm of the apex or in whom the heart is pushed against the chest wall by a high diaphragm (ascites) or a retrocardiac tumor

Thrills. With the hand placed lightly over the precordial region of a subject breathing lightly or, even better, in expiratory apnea, one can perceive *four* types of thrills

1. *Precordial cardiopulmonary rhonchi and wheezes* These are prolonged vibrations which are connected with the phases of inspiration and expiration but are at times only related to cardiac systole due to cardiopulmonary influences. They are present only in bronchopulmonary diseases (acute or chronic bronchitis, bronchial asthma). In some instances, differentiation of these vibrations from those of thrills due to murmurs is difficult and sometimes impossible

2. *Palpable calcular vibrations* These are almost instantaneous short thrills They are due to sudden tension of the cardiac valves and are, therefore, the tactile impression of the cardiac sounds. When such a vibration is felt at the apex, it indicates an intense 1st sound (emotion; effort, hyperthyroidism, mitral stenosis, atrial fibrillation). If it is felt in the 2d left interspace, it is due to pulmonary hypertension (ductus arteriosus, interventricular shunt) If it is noticed in the 2d right interspace, it is produced by arterial hypertension or an aneurysm of the ascending aorta

3 *Fremitus.* This word is used in medicine to designate the tactile sensation of a basal, precordial, or apical *thrill,* which may be systolic, diastolic, or continuous It is caused by the same vibrations which cause murmurs, especially in patients with severe valvular stenosis or abnormal shunts. Conversely, valvular insufficiency produces a thrill only in patients with severe damage, such as the eversion of an aortic leaflet or the rupture of a mitral chorda.

A *systolic thrill* in the 2d *right* interspace is evidence of aortic stenosis, usually rheumatic; less often it is due to subaortic stenosis (congenital) or a syphilitic aneurysm. A *systolic thrill* of the 2d *left* interspace reveals the existence of a congenital pulmonic stenosis. In both types, the thrill is felt better when the patient is sitting upright, with the trunk leaning forward, and also in forced expiratory apnea

An *apical diastolic thrill,* which is more easily elicited with the patient in left lateral decubitus, is evidence of mitral stenosis. It has a presystolic reinforcement or is only presystolic if there is sinus rhythm; it occurs in early- or mid-diastole in patients with atrial fibrillation

Other possible thrills are the *systolic thrill* of interventricular septal defect; the apical *systolic thrill* of mitral insufficiency (usually due to rupture of a chorda); the *diastolic basal thrill* due to luetic aortic insufficiency with eversion of a leaflet; and finally the *continuous thrill* with systolic reinforcement over the 2d left interspace due to persistence of the ductus arteriosus

4 *Palpable pericardial friction rubs.* These are brief tactile sensations which occupy only a part of systole or diastole, or both, and are caused by the same vibrations which give origin to the audible rubs of pericarditis Only exceptionally are these intense enough to be detected by the palpating hand

CLINICAL EVALUATION OF PULSATIONS OF THE CHEST WALL

TECHNIQUE

Pulsations of the thoracic wall which are helpful in the recognition of heart disease can be ascertained by inspection and palpation without the aid of recording devices Graphs are useful for demonstration of clinically observed pulsatory phenomena and for the study of the underlying hemodynamic events *Palpation* is performed by the examiner standing at the right side of the patient and placing his open hand over the precordium In order to detect an *apical thrust,* the index and middle fingers are pressed firmly against the apical region (Fig 3-11A) Sometimes it is necessary to exert considerable pressure in order to detect an apical thrust hidden by a broad, inelastic rib *Thrills* are best felt with the hand resting lightly on the precordium. Pulsatory phenomena other than the apex beat, such

as the *heaving pulsation of the precordium* caused by enlargement of the right ventricle, are elicited by pressing the base of the lightly dorsiflexed hand against the area to be explored (Fig 3-11B).

PHYSIOLOGICAL FORCES RESPONSIBLE FOR PULSATIONS OF THE CHEST WALL

Pulsations are transmitted to the wall of the chest from the heart, the liver, and the great arteries. Cardiac contraction causes pulsations of the thoracic wall by changes in consistency and shape, locomotions, and reduction in volume of the heart.

Change in Consistency. In systole, there is sudden hardening of the myocardium. This may be felt *as a shock* on palpation of the thoracic wall Combined with movement of the heart, it is an important factor in the production of pulsatory phenomena of the chest wall

Change in Shape of the Heart. During systole, the shape of the flaccid heart is largely determined by the surrounding structures In systole, the heart assumes such shape as is determined by its muscular structure. According to Tigerstedt, that diameter of the cross section of the heart which is greater in diastole is shortened in systole, and vice versa. The heart has the tendency to assume a spherical shape in systole and to increase its curvature. This change in shape is pronounced in animal experiments in which the heart is exposed and the pericardium opened. The heart is then flattened during diastole, and its elliptical base becomes spherical in systole. Increase in the curvature of the heart causes an approach to the anterior thoracic wall. These changes in shape are apparently insignificant under physiological conditions when the chest is closed and the heart is subject to elastic traction by the lungs and to the restraining influence of the pericardium Under pathological conditions, however, the heart may be flattened in the anteroposterior diameter, especially if the right ventricle is markedly enlarged. Systolic increase in the curvature, then, produces a characteristic pulsation in the precordial area This affords a readily recognizable sign of right ventricular enlargement, especially in cases of mitral stenosis, in which enlargement of the left atrium forces the heart toward the anterior chest wall.

Rotation of the Heart. During systole the heart rotates from left to right shifting a larger portion of the left ventricle, especially of its apical area, into frontal position This move-



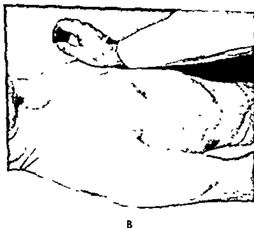


Fig 3-11. A Palpation of the apex beat (From Dressler Clinical Cardiology Hoeber, 1942.) B Palpation of the precordial pulsation caused by right ventricular enlargement (From Dressler. Clinical Cardiology Hoeber, 1942.)

ment is due to the spiral arrangement of the superficial muscle bands The latter, originating in the AV ring, pass obliquely over the anterior surface of the heart and end, by way of forming an inward spiral, in the interventricular septum and the papillary muscles.

Shift of the Apex of the Heart. In systole, the apex of the heart moves caudad. Various factors combine to bring about this movement. In the isometric contraction period, blood moves toward the base of the ventricular cone and closes the atrioventricular (AV) valves. This movement causes recoil of the apex in the opposite direction. A much more powerful ballistic force is created after the opening of the semilunar valves, when the blood is being ejected into the great arteries This force, plus dilatation of the arteries, causes a movement of the apex opposite to the direction of the blood stream, that is, caudad and toward the anterior chest wall

The forces thus far enumerated, namely, hardening of the myocardium, increase in curvature, rotation of the heart, stretching of the large arteries, and recoil of the ventricular cone, tend to produce a propulsion of the thoracic wall during systole These forces are opposed by the effects of systolic diminution in the volume of the heart.

Systolic Diminution in the Volume of the Heart. Decrease in cardiac volume exerts directly and indirectly an *aspiratory effect* upon the wall of the chest A direct aspiratory effect occurs where the heart is in contact with or close to the thoracic wall, if the space opened by the contracting heart is not rapidly filled by the expanding lung Direct aspiration causes *depression* of the precordial area and upward traction of the left leaf of the diaphragm on which the heart is resting On fluoroscopy, this pulsatory movement of the diaphragm is often indicated during systole by a brisk upward shift of the horizontal fluid level in the stomach.

An indirect aspiratory effect is due to a drop in intrathoracic pressure which results from rapid outflow of blood from the chest during systole. Two factors tend to compensate for the outflow of blood; namely, suction of air into the lungs and flow of venous blood into the chest. When these factors are inadequate to prevent a fall in the intrathoracic pressure, an indirect aspiratory action is exerted upon the wall of the chest. This causes a depression of the thoracic wall beyond the boundaries of the precordium, and upward traction of both halves of the diaphragm, both during systole.

The combined effect of propulsion and aspiration, simultaneously acting upon the chest wall during systole, results in a variety of movements of this wall which sometimes are so complex as to defy analysis. In general, it can be said that propulsive movements of the chest wall may be expected to occur when the heart is greatly enlarged and is in broad contact with the thoracic wall. On the other hand, aspiratory effects will predominate when systolic diminution in the volume of the heart is unusually marked.

NORMAL PULSATIONS

The Apex Beat. Under physiological conditions, the predominating pulsatory movement of the thoracic wall is the apex beat or apical thrust. It should be understood that it is usually not the apex proper but an area in the lower third of the frontal aspect of the left ventricle which is thrust towards the wall of the chest during systole. This area is located 2 to 5 cm above the apex and somewhat inside the left margin of the heart.

Of the various forces responsible for the apical thrust, rotation of the heart is most important, according to Wiggers. Other determining factors are the ballistic forces and stretching of the big arteries, all of which cause a shift of the apical portion toward the chest wall during systole.

The view is widely held that an apex beat is a common finding in normal persons. Yet, when one is called upon to demonstrate this pulsation to students, it is surprising how long one has to search even in a large hospital ward for a person with a normal heart displaying an apex beat According to Niehaus and Wright, an apex beat is present in less than 25 per cent of normal individuals, all age groups and both sexes being considered. It is quite common in children and adolescents but, after the age of 20, its frequency rapidly decreases. In adults who are examined in a reclining position, an apex beat is only exceptionally observed, usually in thin individuals with long, flat chests

The heart must be sufficiently close to the thoracic wall to transmit its movements to the

chest. This condition is fulfilled in *young persons*, where the capacity of *the chest* is relatively small in proportion to the size of the heart, *and a high position* of the diaphragm *causes close* juxtaposition of the heart to the thoracic wall. With *advancing age*, the capacity of the chest increases out of proportion to the growth of the heart, and the diaphragm descends. Hence, in adults when reclining, a thick layer of lung tissue usually covers the heart and prevents the apical region from transmitting its movement to the anterior chest wall.

Pulsations of the Chest Wall to the Right of the Apical Region. The propulsive movements of the heart are primarily an effect of left ventricular action. Therefore, they are manifest mainly over the left part of the precordium where they neutralize and even overcompensate the aspiratory effect caused by systolic diminution of the volume of the heart. Farther to the right, over the area of the right ventricle and in the right half of the anterior chest wall, another pattern of pulsation emerges. There, the propulsion is feeble and aspiration, due to reduction of cardiac volume, is the predominating factor. Palpation in these areas, especially palpation of *young persons* with thin, flexible ribs, frequently reveals a *depression* of the thoracic wall during systole. The depression is often most pronounced over the lower portions of the right half of the chest, where the right lobe of the liver *transmits its* pulsation to the thoracic cage.

PATHOLOGIC PULSATIONS

Enlargement of the Heart. Hypertrophy increases the force of cardiac contraction, but does not usually by itself change the pattern of pulsation, except in thin, flat-chested individuals whose heart is close to the thoracic wall. When *dilatation* is added to hypertrophy causing an approach of the heart to the chest wall, conditions are more favorable for transmission of *the forceful* cardiac impulse to the wall of the thorax.

HYPERTROPHY AND DILATATION OF THE LEFT VENTRICLE. *Marked enlargement of the left* ventricle is indicated by a *broad heaving apex beat*. This sign *may* not be apparent for *many* years in patients with hypertensive heart disease or *aortic stenosis*, as long as hypertrophy is of the concentric type. Later on, when dilatation of the left ventricle is marked, a powerful apex beat develops. Its impact is directed not only forward but also laterally, and it may be strong enough to cause a jerky shift of the whole thorax from right to left. Unless marked pressure is exerted on the ribs by the hands of the examiner, even a powerful apex beat may be missed if the thrust is directed toward a broad inelastic rib instead of the intercostal muscles.

The finding of a broad heaving apex beat narrows the field of diagnostic considerations to those few conditions which are characterized by left ventricular hypertrophy. Moreover, it renders other diagnostic methods, such as radiography and electrocardiography, dispensable, when these diagnostic facilities are not readily available. Hypertensive heart disease is the most frequent cause of a heaving apical thrust; it may be diagnosed on *the basis of* this finding even after the blood *pressure has* fallen to normal values, if other less frequent causes, such as lesions of the aortic valves, mitral regurgitation, aortic coarctation, and patent *ductus arteriosus*, have been excluded.

In the selection of cases of mitral stenosis for commissurotomy, it is of great importance to evaluate the degree of associated mitral regurgitation. When a circumscribed heaving *thrust is* found in the apical area in the *absence of other* causes of left ventricular hypertrophy, mitral regurgitation of significant *degree* should be suspected. This is usually considered a contraindication to *surgery*.

HYPERTROPHY AND DILATATION OF THE RIGHT VENTRICLE. An "epigastric pulsation" is generally considered a sign of enlargement of the *right* ventricle. This statement requires *qualification*. In most instances of right ventricular hypertrophy observed by the author, the *epigastric* pulsation did not differ essentially from that occurring in normal individuals, its *prominent* feature is a depression during systole. Only in exceptional cases, when right ventricular enlargement is *severe, does the* heart descend, and the impact of the large right ventricle can be *felt* as a *systolic thrust* in the uppermost portion of the epigastrium. Thus, the *epigastric* pulsation is of little help in the *diagnosis of less advanced* stages of right ventricular enlargement.

The characteristic feature of hypert[illegible] associ[illegible] is [illegible]

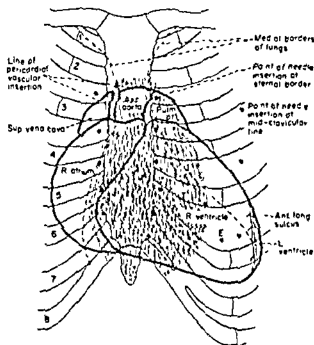


Fig. 3-12. The drawing shows the anterior wall of the heart and its topographic relation to the anterior *thoracic wall* in a case of tight mitral stenosis. The area of pulsation caused by the enlarged right ventricle is indicated by shading (From Dressler, Clinical Cardiology. Hoeber, 1942.)

felt best in that area of the precordium which is *adjacent to the left sternal margin* The right ventricle expands primarily in a transverse direction, in which the elastic cushions of the lungs offer less resistance than the bony structures of the anterior and posterior chest walls The heart is therefore flattened in diastole, especially when, in the presence of mitral valve lesions, it is forced towards the anterior thoracic wall by a dilated left atrium Increase in the curvature of the heart during systole causes a forward lift of the overlying chest wall The pulsation is felt most distinctly when the base of a dorsiflexed hand is pressed forcefully against the costal cartilages of the left 4th to 6th ribs (Fig. 3-11B). Although the pulsation of the enlarged right ventricle is usually most forceful between the sternum and left parasternal line, it may cover a wider area between the 3d rib and the left costal arch, including the sternum and occasionally all of the precordium as far as the left midclavicular line (Figs. 3-12 and 3-13A).

A heaving precordial pulse is most often observed in cases of *mitral stenosis.* Indeed, it is almost pathognomonic of a mitral valve lesion, and its presence in cases of mitral stenosis invariably indicates a marked degree of narrowing of the mitral ostium Therefore, this sign is of serious prognostic import and it represents a useful criterion in the selection of cases for surgical treatment of mitral stenosis.

The characteristic pulsatory sign of right ventricular enlargement is usually missing in congenital lesions with concentric hypertrophy of the right ventricle such as *pulmonary stenosis* The same holds true of *primary pulmonary hypertension* prior to the development of congestive failure. In all these conditions, a heaving pulsation of the precordium may appear in a later stage, when dilatation of the right ventricle develops On the other hand, in certain conditions, where hypertrophy of the right ventricle at the outset is associated with dilatation, as in *pulmonary regurgitation* or *interatrial septal defect*, a heaving pulsation of the precordium may be present at an early stage of the disease. In interatrial septal defect, which is sometimes associated with a marked rotation of the heart to the left, the maximum pulsation may be felt close to the left midclavicular rather than parasternal line.

Mitral Regurgitation Associated with a Huge Left Atrium. In some cases of marked mitral regurgitation, when the left atrial myocardium is largely converted into fibrous tissue, dilatation of the left atrium assumes huge proportions The capacity of the left atrium may increase to 1,000 ml or more. The expanding left atrium grows first in a dorsal direction and then toward the right side. Embracing the right atrium from behind, it may appear in the frontal aspect of the heart and form part or all of its right contour. In the latter case, x-ray study may reveal a *double contour* at the right side of the cardiac silhouette, the darker inner shadow being formed by the right atrium, and the outer arch by the overlapping left atrium.

The jet of blood regurgitating from the left ventricle into the huge left atrium may cause *a striking pulsation of the right half of the chest* It is usually most forceful in the 4th intercostal space on the right midclavicular line The pulsation may extend cranially to the right clavicle and laterally as far as the right axilla In exceptional cases, the whole chest, indeed all of the body, may be shaken by the force of this pulsation. In contrast, marked

diminution of the volume of the left ventricle and diffuse expansion of the right half of the chest during systole are bound to exert an aspiratory effect upon the left hemithorax Thus, a depression of ribs and intercostal muscles at the left half of the chest results; this depression may even involve the lower ribs at the dorsal and lateral aspects of the left half of the chest, producing *Broadbent's sign* in the absence of adhesive pericardial disease and causing a movement of the chest from left to right during systole.

Adhesive Pericarditis. The normal pulsatory pattern of the chest during systole consists of a *forward lift* of the left portion of the precordium and a *depression* of the right side of the chest. This pattern is reversed, not only in mitral regurgitation with huge left atrium, but also in adhesive pericarditis and in severe tricuspid regurgitation.

Normally, the aspiratory effect of cardiac systole over the left portion of the precordium is counteracted by those forces which tend to lift the precordial area When the forces of propulsion, e g, rotation and recoil of the heart, are inhibited by pericardial adhesions, aspiration caused by cardiac systole predominates

The aspiratory effect of cardiac systole is further enhanced in adhesive pericarditis by two factors. Systolic diminution of volume is achieved under normal conditions largely by

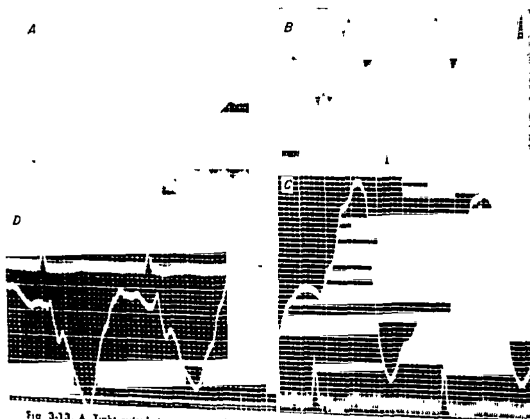


Fig 3-13. A Tight *mitral stenosis* proved by surgery. The upper tracing was taken from the 4th intercostal space on the left parasternal line. The upper curve rises steeply at the onset of systole and forms a plateau corresponding to the palpable systolic pulsation. Electrocardiogram below. (From Dressler, Kleinfeld, and Ripstein J.A.M.A., 1954) B *Constrictive pericarditis* proved by surgery The upper tracing was taken from the 5th intercostal space in the left midclavicular line It shows a depression during systole and a steep rise overshooting the base line in early diastole (diastolic heart beat), electrocardiogram below. C. Tight mitral stenosis and marked tricuspid regurgitation Upper graph of liver pulse shows marked elevation during systole; electrocardiogram below. D Same case Lower graph taken over the 4th interspace in the left midclavicular line shows a distinct depression during systole, electrocardiogram above. (*From Dressler, Kleinfeld, and Ripstein J.A.M.A., 1954.*)

shortening of the ventricular cone, that is, by descent of the base, while centripetal marginal movements of the heart play only a minor role. When, however, the base of the heart is fixed by adhesions and the apical region is free, the marginal excursions increase and the apex moves toward the base in systole in order to ensure an adequate output. In such instances, fluoroscopy reveals large rather than small pulsations of the left ventricular contour. The lengthening of marginal excursions and the motion of the apex toward the base result in an enhanced direct aspiratory effect upon the chest wall This effect is further exaggerated by a second factor, namely, the obliteration of the costomediastinal sinus that is often associated with adhesive pericarditis and prevents the lungs from swiftly filling out the space opened by the contracting heart

A *systolic depression at the left half of the chest* is often the first sign of adhesive pericarditis (Fig. 3-13B) The depression is diffuse and involves the ribs as well as soft parts. It is usually most pronounced in the 4th and 5th intercostal spaces in the left midclavicular line In rare instances, when the heart is fixed (by extensive adhesions) to the posterior portions of the diaphragm, a retraction of the left lower ribs in the dorsal and lateral aspects of the chest is observed This phenomenon, known as *Broadbent's sign*, is by no means specific for adhesive pericardial disease It is occasionally associated with tricuspid regurgitation and, as was mentioned before, with a huge left atrium acompanying mitral regurgitation

The systolic depression of the precordial area is often less impressive than the diastolic rebound of the chest wall (Fig 3-13B) This positive pulsation, which occurs early in diastole, is caused by the impact of blood rushing from the high pressure region of the atria into the ventricles after opening of the atrioventricular valves. Indeed, a *diastolic heart beat* may be readily mistaken for the normal systolic impulse unless it is properly timed by comparison with the arterial pulse.

Tricuspid Regurgitation. In cases of mitral regurgitation the affected chambers are chiefly located at the back of the heart and are inaccessible to direct study, but conditions are much more favorable for direct clinical observation in cases of tricuspid regurgitation The enlarged right ventricle, the atrium, and the liver are in broad contact with the thoracic wall; thus, the dynamics of tricuspid regurgitation can manifest themselves by characteristic pulsations which may be noted on inspection and palpation of the anterior and lateral chest walls.

The right ventricle throws a quantity of blood back into the right atrium and the large veins with each systole. Most of the backflow is directed toward the liver since the hepatic veins have no valves to block the regurgitating stream. Its impact causes *a forceful propulsion of the right lower half of the chest* which overlies the liver. Sometimes the impact is strong enough to lift the whole right half of the chest during systole This pulsation is felt best with a fist firmly pressed against the lower ribs over the right midaxillary line. The finding of a systolic propulsion of the bony structures covering the liver affords dependable evidence of tricuspid regurgitation in those patients where the liver is not yet sufficiently enlarged to be palpated below the costal arch, or is not accessible to palpation because of meteorism, ascites, or rigidity of the abdominal wall.

When tricuspid regurgitation is marked, the left half of the chest presents a pulsation which is opposite in direction to that of the right side. A *systolic depression* (Fig 3-13D) may involve nearly all of the left anterior and lateral portions of the thoracic cage. Various factors contribute to this pulsation: the greatly dilated right ventricle together with the right atrium may form the whole anterior aspect of the heart, the left as well as the right contour of the cardiac silhouette. Marked systolic diminution in volume of the right ventricle is identified, on fluoroscopic examination, by wide pulsatory excursions of the left border of the heart Lengthened pulsatory excursions result in an enhanced direct aspiratory effect which causes depression of the precordium during systole.

The indirect aspiratory effect of cardiac systole is also increased in tricuspid regurgitation A large portion of the increased output of the right ventricle, instead of going into the lungs, leaves the chest cavity and flows backwards, mainly into the liver. Thus, an abnormal drop in the thoracic pressure results during systole It cannot be quickly balanced by influx

of blood into the thorax, because the blood in the veins moves centrifugally during systole. Hence, a powerful indirect aspiratory effect produces *a diffuse depression of the left anterior and lateral portions of the chest wall.* In rare instances, even the lower ribs of the dorsal and lateral aspects of the chest may be involved. If one places one hand over the right half of the thorax and the other hand on the left side of the chest, *a seesaw movement* can be palpated if marked tricuspid regurgitation is present. One virtually feels how the blood is thrown to and fro between the right ventricle and the liver.

The pathognomonic sign of tricuspid regurgitation is *an expansile pulsation of the liver during systole* (Fig. 3-13C). Nevertheless, many clinicians hesitate to make the diagnosis of tricuspid regurgitation because they feel that a systolic hepatic pulse may be simulated by a pulsation transmitted from a hypertrophied right ventricle or from the abdominal aorta. Clinical and graphic study of the hepatic pulse consists essentially of a systolic depression, which is caused by a cranial movement of the whole organ and outflow of venous blood from the liver, due to the aspiratory effect of cardiac systole. This pulsatile pattern is maintained in the presence of marked right ventricular hypertrophy, as well as aortic regurgitation, in which the pulsation of the abdominal aorta is greatly increased. Tricuspid regurgitation can be safely diagnosed when palpation, either of the hepatic surface or of the lower ribs overlying the right hepatic lobe, reveals *a forceful systolic forward lift.* To be sure, the differentiation between organic and relative tricuspid regurgitation is difficult if not impossible for the clinician to make in most instances.

THE KINETOCARDIOGRAM—ULTRA LOW-FREQUENCY PRECORDIAL MOVEMENTS

The chest wall is set into vibration with each heart be[illegible] abo[illegible] phy[illegible] marily associated with the movements of the various intracardiac valves. On the other hand, there are vibrations of the precordium that cannot be heard (about 1 to 30 cps) *but can* be palpated or seen. These ultra-low-frequency waves are slow displacement movements *of the* precordium that are related *primarily to the* movements of the heart rather than to valvular events. The exaggerated apex impulse, due to left ventricular hypertrophy, and the parasternal lift, often noted in patients *with a right* ventricular hypertrophy, are two such examples.

The apex impulse has been graphically studied by *numerous investigators*, their work dating back to 1885, when Marey recorded the movements by the use of a capsule. This was later modified by Cushney so that the vibrations of a tambour could be photographed. Similar records were reported by Weber, Weitz, Hess, and others. In addition, numerous records have appeared in the literature of the apex beat illustrating certain aspects of cardiovascular dynamics. The most extensive work was that of Dressler (1933), who prepared a monograph, as well as a series of other articles. Johnston and Overy (1951) and Luisada and Magri (1952) presented a group of representa*tive records* from normal subjects and from patients *with* various types of heart disease. *These studies* renewed interest in ultra-low-*frequency* precordial movements; since then, a *number of studies* have been reported as well as new and different recording techniques. *When these* movements are recorded from a fixed point above the chest wall, the records *have* been termed "kinetocardiograms." The *differences* between these types of records and those obtained with pickup devices that rest upon the chest wall will be discussed subsequently.

METHODS

Various *methods* have been used for recording ultra-low-*frequency* precordial movements. Table 3-2(1) *presents* a summary of some of those recently reported, along with data on a few methods that yield *records* other than displacement. Even though many *types of transducers* and sensing devices have been used, in *general* the tracings are similar as long as certain principles are adhered to: (1) the device must sense *and record* only displacement, (2) the *frequency response* of the system should be linear, at least between 0.5 and 50 cps, and (3) the sensing probe should have sufficient excursion to record the large displacement movements often encountered in disease states. The only *problem* concerns the type of

TABLE 3-2(1). SYSTEMS FOR RECORDING ULTRA-LOW-FREQUENCY PRECORDIAL MOTION

Reference	*Transducer*	*Chest piece*	*Type of mount*	*Frequency response*	*Type of signal*
Johnston and Overy	Electromanometer	Funnel (end piece of Boweles type)	Directly on chest wall	Subaudible range (presumably 1 cps and above)	Displacement
Luisada	Linear microphone	Funnel (5 cm)	Directly on chest wall	Low (presumably 1 cps and above)	Displacement
Eddleman	Piezo-electric transducer † or P5A Statham strain gauge	Bellows	Cross bar—from a fixed point above the chest wall	0-75 cps	Displacement (kinetocardiograms)
Groom*, et al	RCA electronic tube 5734 with a special circuit	Diaphragm with probe attached to center	Directly on chest wall	2-500 cps (2-50 cps in low range)	Displacement
Dimond	Linear microphone	Microphone pickup bell	Directly on chest wall	1-1,000 cps (frequency response of crystal microphone)	Displacement
Schneider and Kunhaar	Differential transformer	Transducer and probe	Directly on chest wall	0-70 cps	Displacement
Other related systems—records not similar to those above					
Rosa, et al	Condenser microphone	Microphone	On chest wall	5-25 cps	Acceleration(?)
Mounsey, et al	Mercury accelerometer	Accelerometer used directly	On chest wall	0-3,000 cps	Acceleration
Agress	Altec-Lansing capacitance microphone (165A)	Microphone	From a horizontal bar over bed or directly on chest wall	(System to display various frequency ranges with analyzer)	Not stated—presumably acceleration

* Because of a filter set at 2 cps records not entirely similar to kinetocardiograms.
† No longer used because of the decay in the signal at very low frequencies, although in most records this is of no significance.

mount, not specifically the transducer Most investigators have placed the transducer directly on the chest wall, in the kinetocardiographic technique the pickup (bellows) is suspended from a fixed point above the chest wall (Fig 3-14). Although there is no definitive evidence as to which type of mount is superior, theoretical considerations would seem to favor suspending the sensing unit from a fixed point above the chest wall, for the following reasons (1) Any device that rests upon the chest wall responds to the differential motion between the part of the transducer that touches the chest wall and the sensing probe, therefore, some changes in the configuration and time sequence of the various movements may result. (2) If the chest-wall motion arrives at the rim before it reaches the sensing probe, a shift in phase will occur, and the resulting record may be a velocity rather than a displacement tracing (3) The configuration of the records may vary according to the size and diameter of the rim, and according to the size of the mount that rests upon the chest wall. Since the size of the various types of transducers has not been standardized, comparison of the tracings from various laboratories may be difficult (4) Large, diffuse precordial movements may be minimized or poorly registered by a pickup that rests on the chest wall, since the rim and sensing probe will move together as a unit. For example, the parasternal lift due to right ventricular hypertrophy may be recorded as a small outward movement when in reality it may be large Using a fixed point above

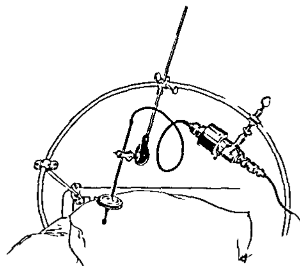


Fig. 3-14. Kinetocardiographic apparatus used by the author. Note that the bellows is connected to a P5A Statham strain-gauge transducer with a short piece of plastic tubing, all of which is mounted on a crossbar above the bed. This makes it possible to record absolute chest-wall motions, free of distortion, obtaining true ultra-low-frequency precordial records.

the chest wall to mount the pickup ensures reproducibility, lack of phase distortion, and pure displacement tracings, graphically similar or identical to the movements felt or seen at the bedside The differences encountered in the records made by the various displacement techniques, whether or not the sensing unit rests upon the chest wall, are usually minimal except in certain instances as mentioned, and, in general, the data from one type of system can be transferred to others. However, the data from detailed kinetocardiographic studies concerning the genesis of the movements as well as those which standardize certain measurements probably cannot be applied to the tracings obtained with other methods.

TERMINOLOGY AND NORMAL RECORDS

Neither a uniform way of designating the precordial recording positions nor a standard nomenclature for the various movements encountered in ultra-low-frequency tracings has been devised or accepted However, the following scheme can easily be applied and appears to be the simplest

Tracings taken from the various standard precordial electrocardiographic V lead positions are designated by the letter "K" instead of "V" to signify the difference Thus K_1 is the record obtained from the V_1 position—the right parasternal region of the chest wall in the 4th intercostal space, and K_2, the record obtained from the V_2 position—the left parasternal region in the 4th intercostal space Tracings taken from other intercostal spaces can be designated with an additional subscript For example, K_{22} represents the record from the left parasternal region of the chest in the 2d intercostal space, K_{12}, the record from the right parasternal region in the 2d intercostal space, K_{13}, the record from the right parasternal region in the 3d intercostal space, etc The epigastric tracings have usually been obtained from a point just beneath the subcostal margin in the right and left midclavicular lines and may be designated KER and KEL, respectively The tracing taken from the midepigastric region, just below the xiphoid process of the sternum, may be designated as KEM Figures 3-15 to 3-17 are idealized drawings of the normal K_1, K_2, and K_3 records. The K_4 tracing is not presented, as it is similar to the K_3 Whenever possible, a nomenclature is presented that relates the movement to its genesis When the mechanism (or mechanisms) is less certain, the movements have been designated by identifying terms usually related to time in the cardiac cycle, and the apparent origins are listed as secondary terms The genesis of the various movements in the normal kinetocardiogram, as listed in Figs 3-15 to 3-17, is taken from an extensive indirect correlative study by Harrison and coworkers (1959a), the reader is referred to several recent publications for a complete discussion (Coghlan et al, Prieto et al; Harrison et al, 1959a). These conclusions should be considered tentative until proved or disproved by more direct techniques In addition, somewhat different designations, used in relationship to an arbitrary base line, are useful in defining certain abnormalities. *The base line is drawn horizontally at a point on the curve which is 0 01 sec after the onset of the QRS complex in the electrocardiogram.* This point was chosen because it is close to the time when most of the ventricular components of the kinetocardiogram begin.

Attention is directed to certain movements: (1) *The right parasternal upstroke or the right ventricular movement* (Fig. 3-15). The movement begins in normal subjects at about 0 05 sec after the onset of the QRS complex in the electrocardiogram and is normally a brief, small outward movement. It becomes markedly exaggerated as the result of increased right ventricular pressure or flow load, and may be present in such circumstances over the entire right and left precordial areas. (2) *Left ventricular thrust* (Figs. 3-16 and 3-17). This movement probably results from a recoil force, as ejection begins, in normal subjects, and is exaggerated both in amplitude and duration in patients with increased left ventricular flow or pressure load. The abnormality noted in patients with left ventricular disease is probably related to other factors in addition to recoil. (3) *Total systolic retraction* (Figs 3-15 to 3-17). This is the marked inward movement of the chest wall during most of the ejection phase It is probably due to the decrease in heart size which is associated with the ejection of blood, and possibly to changes in intrathoracic pressure, both of which may result in retraction of the chest wall. (4) *The filling movement* (Figs. 3-16 and 3-17) The onset of the filling movement is synonymous with the opening snap in patients with mitral stenosis The physiologic 3d heart sound and the protodiastolic gallop occur near the peak, or top, of the movement, as would be expected (5) *The atrial movements* (Fig 3-15) These are small, slow movements in normal subjects, beginning after the onset of the P wave and ending shortly after the onset of the QRS complex in the electrocardiogram They may be noted in patients with complete heart block following each P wave

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* Because of a filter set at 2 cps records not entirely similar to kinetocardiograms

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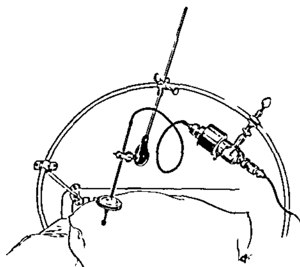


Fig. 3-14. Kinetocardiographic apparatus used by the author. Note that the bellows is connected to a P5A Statham strain-gauge transducer with a short piece of plastic tubing, all of which is mounted on a crossbar above the bed. This makes it possible to record absolute chest-wall motions, free of distortion, obtaining true ultra-low-frequency precordial records.

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movement (bulge); (3) providing a rough method to estimate gross changes in pulmonary artery pressure and total pulmonary vascular resistance, (4) helping to recognize significant mitral insufficiency in the presence of mitral stenosis, (5) following patients with right ventricular overload as an objective method in demonstrating the progress of the disease, (6) evaluating postoperatively patients with mitral stenosis, (7) evaluating therapy for congestive heart failure; (8) identifying (as a reference tracing) certain cardiovascular sounds; (9)

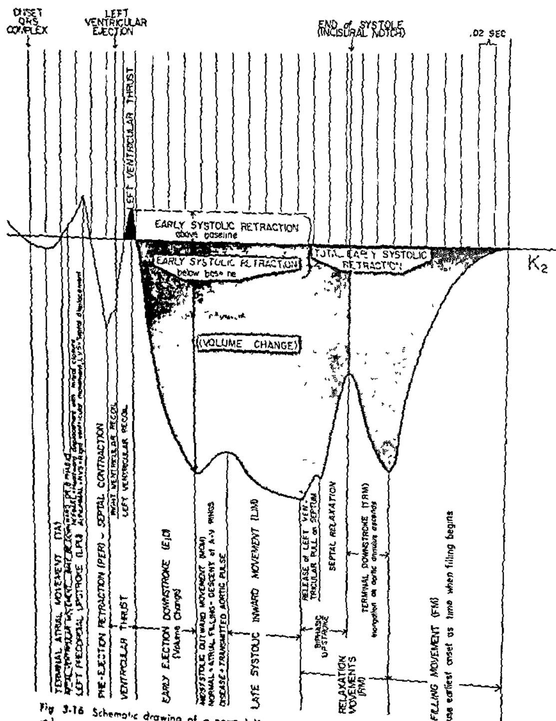


Fig 3.16 Schematic drawing of a normal K_2 record. (See text, page 3-65(Supp)) (From an indirect study of the normal kinetocardiogram by Harrison et al)

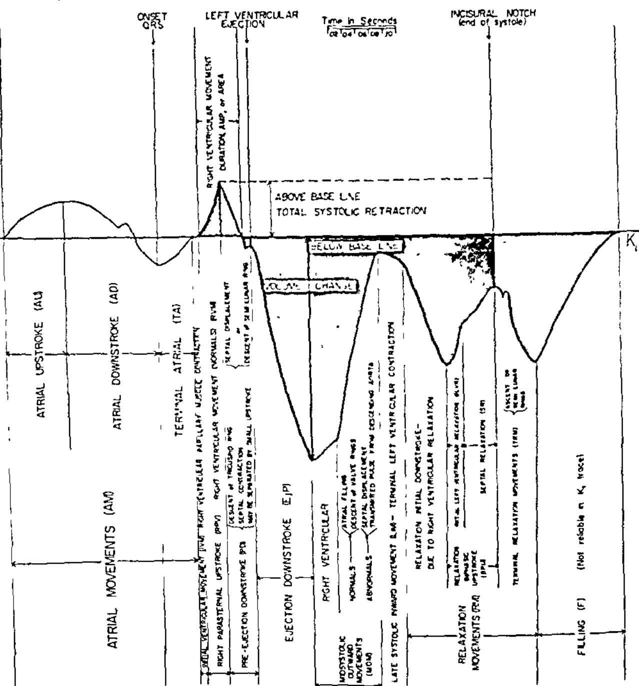


Fig. 3-15. Schematic drawing of a normal K_1 record (See text, page 3-65[Supp]) (*From an indirect study of the normal kinetocardiogram by Harrison et al*)

CLINICAL USE OF THE KINETOCARDIOGRAM

As some of the ultra-low-frequency precordial records look similar in the various cardiovascular disease states, it is important to appreciate that, except in a few instances, the kinetocardiogram alone cannot be used for making a specific anatomic diagnosis. Like many other laboratory procedures, it must be used clinically by integrating the findings with other clinical data. Since it is uncertain whether or not hypertrophy of the ventricle is responsible for the kinetocardiographic abnormalities associated with the various types of pressure and flow loads on the ventricles, the alterations will be referred to as *left or right ventricular overload* or *combined ventricular overload*, not as "hypertrophy."

The tracings may be of clinical value in (1) confirming or evaluating left or right ventricular overload or their combination; (2) providing supplemental evidence of a myocardial infarction by the presence of a paradoxic outward

movement (bulge), (3) providing a rough method to estimate gross changes in pulmonary artery pressure and total pulmonary vascular resistance, (4) helping to recognize significant mitral insufficiency in the presence of mitral stenosis; (5) following patients with right ventricular overload as an objective method in demonstrating the progress of the disease, (6) evaluating postoperatively patients with mitral stenosis, (7) evaluating therapy for congestive heart failure; (8) identifying (as a reference tracing) certain cardiovascular sounds; (9)

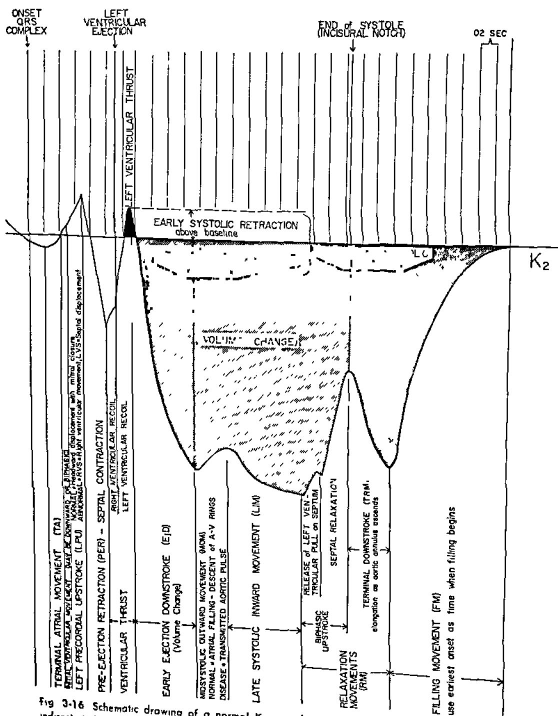


Fig 3-16 Schematic drawing of a normal K_2 record (See text, page 3–65[Supp]) (From an *indirect study of the normal kinetocardiogram* by Harrison et al)[7]

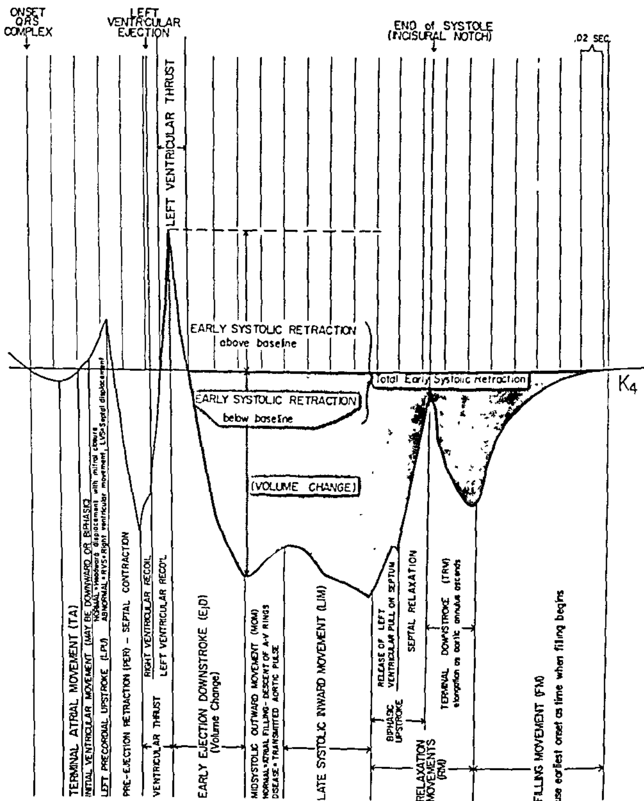


Fig. 3-17. Schematic drawing of a normal K_3 record. (See text, page 3–65[Supp.]) *(From an indirect study of the normal kinetocardiogram by Harrison et al.)*

training a physician in palpation of the precordium, and (10) providing a technique for physiopathologic investigations

Right Ventricular Strain. Figure 3-18 presents a drawing of the kinetocardiographic abnormalities due to increased right ventricular pressure and flow loads Note that the right ventricular movement becomes exaggerated both in amplitude and in duration, however, flow loads have an exaggerated total systolic



Fig 3-18. *Schematic drawing showing the various degrees of kinetocardiographic abnormality due to right ventricular pressure and flow loads* The right ventricular movement is indicated by a *curved arrow.* Note that in the flow loads *the* systolic retraction (*vertical line*) is markedly exaggerated, whereas the records obtained from patients with *pressure* loads have an exaggeration of sustained midsystolic movement due to right ventricular activity resulting in a prominent sustained outward *precordial* movement. These tracings *are usually* most prominent in the lower parasternal region of the chest (K_1 and K_2) but *may* be noted as far to the left as K_3. The features illustrated are more *commonly* noted in patients with *mitral stenosis,* idiopathic pulmonary hypertension, and interatrial septal defects The same general features are often noted from patients with *cor pulmonale.* However, in these patients the *epigastric* records often demonstrate an *exaggerated early-systolic outward* movement which *is more* prominent than that of the lower parasternal region of the chest In addition, some of the congenital heart diseases apparently do not fit well into the scheme as presented.

retraction, probably because of the large stroke volumes (Eddleman et al., 1959a). The right ventricular movement during midsystole (Figs. 3-15 and 3-18) becomes exaggerated in patients with pressure loads, resulting in a large midsystolic outward movement. The right ventricular overload pattern is usually most pronounced in the K_1 and K_2 records, producing the lower parasternal lift characteristically felt in these patients at the bedside. However, it may be present in the K_4 record. Table 3-2(2)

TABLE 3-2(2) LOCATION OF LARGEST OUTWARD MOVEMENT IN 46 PATIENTS WITH MITRAL STENOSIS

	Percentage
K_1	22
K_2	57
K_3	15
K_4	6
K_5	0

presents the location of the largest outward movement as taken from a group of 46 patients with only mitral stenosis. Note that 22 per cent have the maximal impulse at the K_1 position, and no impulse at the K_5 position. This is of help in differentiating right from left ventricular overload.

In addition to the pattern abnormalities, certain measurements are of help in analyzing the records. The right ventricular ratio (obtained by dividing the amplitude of the right ventricular movement in the K_1 record by the total systolic retraction—Fig. 3-19) is of some

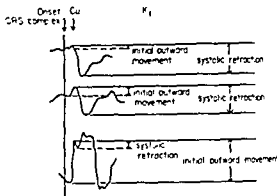


Fig. 3-19. *Schematic drawing of a method used in obtaining the right ventricular ratio from the K_1 tracing. Amplitude of the initial outward movement or right ventricular movement is divided by the amplitude of the systolic retraction, as illustrated. The ratio obtained makes it possible to avoid using absolute amplitude units, since the amplitude of the tracing varies according to the structure of the chest wall. This ratio is useful in evaluating right ventricular function and possibly in estimating pulmonary artery pressure. (Courtesy of The American Journal of Cardiology.)*

help in recognizing right ventricular abnormalities. Table 3-2(3) presents some features that aid in delineating right ventricular overload.

Left Ventricular Overload. Increased pressure and flow loads in the left ventricle result in an exaggeration in amplitude and duration of the left ventricular thrust. Figure 3-20(1)B illustrates the abnormalities as usually encountered. The preejection retraction movement (PER) is gradually lost, and the true thrust fuses with

TABLE 3-2(3) SOME DISTINGUISHING FEATURES OF RIGHT VENTRICULAR OVERLOAD *

Description	*Finding*	*Significance*
Initial left precordial upstroke	Duration 0.09 sec or longer	Not specific but probably indicates right ventricular strain
Right ventricular ratio (K_1)	0.80 or longer	Probably right ventricular strain if severe biventricular failure is excluded
Right ventricular ratio (K_1)	1.00 or longer	Probably right ventricular strain
Point of largest outward movement	Located at K_1	Right ventricular strain
Point of largest outward movement	Located at K_5	Not right ventricular strain (excluding congenital heart disease)
Point of largest outward movement	Located at K_2	Right ventricular stress (if ischemic heart disease is excluded)
Left precordial upstroke	K_2—0.05 sec greater than K_4	Probably right ventricular strain
Left precordial upstroke	K_4—0.05 sec greater than K_2	Probably not right ventricular overload

* The clinical significance of the findings as listed can be used only as a general guide

the initial left precordial upstroke, forming one large sustained outward movement during systole The maximal thrust not only is located at K_4 and K_5 but may be present at K_3 as well However, in a group of 115 patients with *arterial diastolic hypertension or aortic valvular disease*, no instance was encountered where it was maximal at the K_2 point Table 3-2(4) lists the distribution of the largest outward movement (LVT) at the various points over the precordium, and, for contrast, the location of the largest outward movement from patients with mitral stenosis No patient with mitral stenosis had a maximal impulse at K_5, and no patient with left ventricular strain had a maximal impulse at K_1 or K_2

The abnormalities may also be defined by the duration of the left ventricular thrust on the base line. A maximum impulse of 0 09 sec or greater has more than a 95 per cent chance of being abnormal. Using this criterion, 87 per cent of the group of patients with left ventricular stress have abnormal records Kinetocardiographic correlations with the heart size measurements and electrocardiographic findings in a [illegible]

[illegible] Table 3-2(5) lists some of the distinguishing features of records due to left ventricular overload

The exact cause for the exaggerated and prolonged *impulse associated with* left ventricular strain is not entirely apparent It is possible that it is related to left *ventricular hypertrophy* as well as to an increase *in amount of left ventricular* work However, *the parallelism* between the abnormality and the functional *state* of the patient is also a factor. *In other words*, the more functionally severe the *condition* of the patient is, the more the impulse will be exaggerated and prolonged; patients who are asymptomatic are less likely to have abnormal records, even though the heart may be enlarged or working under a marked increase in load (flow or pressure). In addition, the abnormal left ventricular thrust is not directly related to heart size Thus the abnormality may be due to the summation of many factors, such as left ventricular hypertrophy, increased amount of

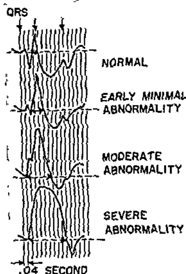


Fig. 3-20. Schematic drawing of the abnormalities of the left ventricular thrust as encountered in patients with left ventricular overload The horizontal base line is drawn at a point on the curve which is 0 04 sec after the onset of the QRS complex in the electrocardiogram The abnormality may then be determined by the duration of the impulse along the base line Any maximum impulse from patients with left ventricular overload that is 0 09 sec or greater is considered abnormal (*Courtesy of the American Heart Journal*)

TABLE 3-2(4) LOCATION OF LARGEST OUTWARD MOVEMENT, PERCENTAGE *

Condition	*No of patients*	K_1	K_2	K_3	K_4	K_5
Mitral stenosis	46	22	57	15	6	0
Arterial hypertension	48	0	0	17 †	79	4
Aortic valvular disease	52	0	0	10	67 ‡	23
Arterial diastolic hypertension and aortic valvular disease	100	0	0	13 †	75 ‡	13

* Includes only those patients [illegible]
† Includes one
‡ Includes three

TABLE 3-2(5) SUMMARY OF RADIOGRAPHIC, ELECTROCARDIOGRAPHIC, AND KINETOCARDIOGRAPHIC DATA IN 115 PATIENTS WITH ARTERIAL DIASTOLIC HYPERTENSION AND AORTIC VALVULAR DISEASE

No. and type of patients	*Radiographic findings*								*Electrocardiographic findings*								*KCG findings*	
	Clinical impression abnormal		*C/T ratio 0.5 or greater*		*Transverse cardiac diameter greater than 115% predicted **		*Frontal area greater than 110% predicted **		*Positive by Grant criteria †*		*Positive by Sokolow criteria ‡*		*Intrinsicoid deflection 0.05 sec or longer*		*Left axis deviation*		*Left ventricular thrust 0.09 sec or longer*	
	No	%	No	%	No	%	No	%	No	%	No	%	No	%	No	%	No	%
60 hypertensive patients	28	47	23†	38	22	37	41	68	27	45	36	60	9	15	3	5	48	80
55 patients with aortic valvular disease									26	47	45	82	19	36	10	18	52	95
Total of 115 patients									53	46	81	70	28	25	13	11	100	87

* According to the standards presented by Ungerleider and Gubner Am Heart J 1942
† Any precordial V lead with a total amplitude (R + S) of 40 mm or greater Individuals under 25 years of age may be exceptions
‡ Standard criteria for left ventricular hypertrophy as presented by Sokolow and Lyon Am Heart J 1949

TABLE 3-2(6) SOME DISTINGUISHING FEATURES OF LEFT VENTRICULAR OVERLOAD *

Description	*Finding*	*Significance*
Left ventricular thrust (point of largest outward movement)	0.09 sec or longer	Greater than 95% chance of being abnormal, indicating left ventricular overload
Point of largest movement	Located at K_1 or K_2	Probably not left ventricular overload
Right ventricular ratio †	Over 0.40 without severe biventricular failure	Tends to exclude left ventricular overload
Right ventricular ratio †	Over 0.80	Excludes left ventricular overload
Point of largest outward movement if at K_4	Duration —between 0.09–0.20	More likely left ventricular overload than paradoxic outward movement due to a myocardial infarction
Duration of paradoxic outward movement	K_4 trace 0.05 sec greater than duration in K_2 tracing	Probably not right ventricular stress but may be either left ventricular overload or infarction

* The clinical significance of the findings as listed can be used only as a general guide.
† See text for definition of right ventricular ratio

work, left ventricular dilatation, and it may be related, in some way, to the functional state of the myocardium

Valvular Heart Disease. Kinetocardiographic tracings of patients with valvular heart disease differ from normal tracings in various ways, depending upon the type of the underlying ventricular abnormality. For example, patients with *mitral stenosis* have records identical to those described for right ventricular pressure loads [Fig. 3-20(1)A]. Patients with *aortic valvular disease* have tracings compatible with left ventricular pressure or flow load [Fig 3-20(1)B] In addition, there are some other pattern differences The majority of patients with *mitral insufficiency* have a prominent late-systolic outward movement over the left precordium [Fig 3-20(1)C] This change is not pathognomonic, as some patients with precordial pain may have a prominent late-systolic outward movement as well (Harrison and Hughes) However, the differentiation between mitral insufficiency and coronary disease with precordial pain is usually not a significant bed-

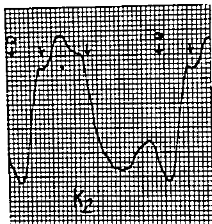
side problem. A few patients with "*pure*" *mitral insufficiency* have only an abnormal and prominent left ventricular thrust, and some patients may have both features. Table 3-2(7) lists the

TABLE 3-2(7) KINETOCARDIOGRAPHIC FINDINGS IN PATIENTS WITH MITRAL INSUFFICIENCY

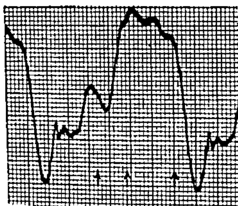
Condition	*No. of patients*
Late-systolic outward movements only .	15
Abnormal left ventricular thrust only . .	4
Late-systolic outward movement and abnormal left ventricular thrust .	3
Total	22

various findings in a group of 22 patients with clinically "pure" mitral insufficiency. Although the degree of mitral insufficiency cannot be accurately estimated by the use of the kinetocardiographic technique, many patients with combined mitral stenosis and significant mitral insufficiency have sufficient abnormality in the tracing (prominent late-systolic movement or an abnormal isolated left ventricular thrust) to suggest the presence of an abnormal left ventricular flow load. In these instances, the kinetocardiogram is useful in directing attention to possibly significant valvular insufficiency, which may warrant further investigation with other methods, such as direct left heart pressure measurements

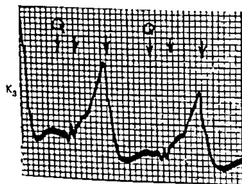
The tracing of a patient with *aortic stenosis* often differs from that of a patient with *aortic insufficiency* in the configuration of the left



A



B



C

Fig 3-20(1) A K_2 tracing from a patient with pure mitral stenosis, showing the marked outward movement during systole. Time lines of this record are 0 02 sec apart The arrow labeled Q indicates the onset of the QRS complex in the electrocardiogram, the second arrow, the upstroke of the carotid pulse; and the third arrow, the incisural notch This illustrates the marked parasternal lift or heave associated with right ventricular pressure loads B Tracing of the maximum left ventricular thrust (K_3) from a patient with severe aortic stenosis (left ventricular pressure load) The time lines are 0 02 sec apart. The first arrow at the lower part of the figure indicates the onset of the QRS complex in the electrocardiogram, the second arrow, the upstroke in the carotid pulse, and the third arrow, the carotid incisural notch Note the marked outward movement which occurs about 0 04 to 0 05 sec after the onset of the QRS complex and which is sustained throughout all systole This is an example of a marked abnormality of left ventricular thrust associated with left ventricular pressure loads C. Tracing taken from a patient with pure mitral insufficiency, illustrating prominent late-systolic outward movement, often noted with this type of valvular defect. The time lines are 0 04 sec apart. The arrow labeled Q represents the onset of the QRS complex in the electrocardiogram, the second arrow, the onset of the upstroke in the carotid pulse, the third arrow, the carotid incisural notch Note that the late-systolic outward movement reaches the peak just before the incisural notch in the carotid pulse

ventricular thrust. Although both have an exaggeration of the left ventricular thrust, the thrust tends to be much more sustained in patients with *aortic stenosis* than in those with *aortic insufficiency*. This is probably because of the large stroke volumes in patients with aortic insufficiency. However, sustained thrusts may be noted in patients with marked left-sided congestive failure, regardless of the underlying causation of the heart disease. Nevertheless, the differences in the duration and configuration of the left ventricular thrust may be of some aid in suggesting a significant stenosis in the presence of aortic insufficiency.

Ischemic Heart Disease. MYOCARDIAL INFARCTION The characteristic change in the kinetocardiogram as the result of a myocardial infarction is the presence of a *paradoxic systolic outward movement* (POM) [Fig 3-20(2)A]. The POM usually begins early in systole (before ejection begins or at the same time). However, in patients with precordial pain, which will be discussed subsequently, the paradoxic pulsation often begins in late systole (late-systolic paradoxic outward movement) The paradoxic outward movements may be classified according to both the time in the cardiac cycle when they begin, and their duration above the baseline as measured on the baseline [Table 3-2(8)].

Table 3-2(9) presents the incidence of paradoxic outward movements in 102 patients with both acute and old myocardial infarction Note that bulges (duration of 0.20 sec or longer) were present in 68 per cent of the patients The location of the POM with the maximal amplitude is of some significance, particularly in differentiating the POM due to myocardial infarction from those of left or right ventricular strain. Table 3-2(10) presents the location of the maximal POM in 69 patients.

As previously stated, the kinetocardiographic tracings cannot be used alone (except in isolated instances) in making a diagnosis. The findings must be considered along with other clinical and laboratory data in order to arrive at a reasonable conclusion. Nevertheless, instances are encountered where the kinetocardiographic tracings are of significant clinical

TABLE 3-2(8). CLASSIFICATION OF SYSTOLIC PARADOXIC OUTWARD MOVEMENTS (POM) DUE TO ISCHEMIC HEART DISEASE

Characteristics	*Early*	*Late*
Onset . . .	Between Q and beginning of ejection	Between onset of ejection and before end of systole
Duration:		
Grade I POM	0.09–0.14 sec	0.09–0.14 sec
Grade II POM	0.15–0.19 sec	0.15–0.19 sec
Grade III POM	0.20+ sec (or early systolic *bulge*)	0.20+ sec (or late systolic *bulge*)

TABLE 3-2(9) INCIDENCE OF BULGES DUE TO MYOCARDIAL INFARCTION

Condition and no of patients	*Bulges, Class III POM* *		*Abnormal movements, Class I and II POM*		*Normal records*	
	No	*Per cent*	*No*	*Per cent*	*No*	*Per cent*
Acute anterior myocardial infarctions, 30	29	81	2	6	5	13
Acute posterior myocardial infarctions, 24	13	62	2	8	9	30
Old anterior myocardial infarctions, 21	12	57	5	21	4	19
Old posterior myocardial infarctions, 21	15	71	0	0	6	29
[illegible]	42	70	4	7	14	23
	27	64	5	12	10	24
	41	72	7	12	9	16
	28	62	2	4	15	33
All infarctions, 102	69	68	9	9	24	23

* Paradoxic outward movements

TABLE 3-2(10). LOCATION OF BULGE OF MAXIMUM AMPLITUDE* IN 69 PATIENTS WITH MYOCARDIAL INFARCTION

Condition	K_2		K_3		K_2 and K_3		K_4		K_5		K_4 and K_5		Elsewhere or areas	
	No.	Per cent†	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent
Anterior infarctions, 41 bulges†	8	20	20	49	25	61	5	12	4	10	9	22	4	10
Posterior infarctions, 35 bulges†‡	4	11	4	11	8	23	8	23	4	11	12	34	18	51
All infarctions, 69 bulges†	12	17	24	35	36	52	13	19	8	12	21	31	12	17

* Includes only those bulges with a duration of 0.20 sec or more; the percentage figures are based upon the

. . . . my ocardial infarction.

TABLE 3-2(11). SOME FEATURES OF THE PARADOXIC OUTWARD MOVEMENT DUE TO MYOCARDIAL INFARCTION

Description	Finding	Significance*
Point of largest outward movement (if right ventricular strain is excluded)	0.20 sec duration at K_4 or epigastric area	Most likely due to myocardial infarction
Point of largest outward movement (if right ventricular overload is excluded)	0.20 sec duration at K_3	Most likely myocardial infarction but left ventricular strain can do this
Right ventricular ratio	Over 0.50 and absence of severe biventricular failure	Probably excludes a bulge
Paradoxic outward movement at K_2 and K_4	K_4 0.05 sec longer than duration at K_3	Probably right ventricular strain and not myocardial infarction

* The clinical significance of the findings as listed can be used only as a general guide.

help. For example, patients with atypical angina-like pain may present the problem of

tion, or at least the presence of ischemic heart disease. In addition, a POM or bulge may

. . . . . . earlier than would otherwise be possible.

Certain differentiating features in the kinetocardiographic tracings may be useful in analyzing the records. Table 3-2(11) lists these differences.

PRECORDIAL PAIN OF SHORT DURATION (ANGINA PECTORIS). Approximately one-third of the patients with this type of pain will have an early-systolic POM, which may or may not meet the criteria of a bulge. An early-systolic POM (bulge) in the resting records probably indicates an underlying myocardial infarction (age undetermined). In addition, these patients may have a late systolic bulge [Table 3-2(10) and Fig. 3-20(2)B]. The mechanism of this abnormality is uncertain at p . . . a

ventricular thrust. Although both have an exaggeration of the left ventricular thrust, the thrust tends to be much more sustained in patients with *aortic stenosis* than in those with *aortic insufficiency*. This is probably because of the large stroke volumes in patients with aortic insufficiency However, sustained thrusts may be noted in patients with marked left-sided congestive failure, regardless of the underlying causation of the heart disease Nevertheless, the differences in the duration and configuration of the left ventricular thrust may be of some aid in suggesting a significant stenosis in the presence of aortic insufficiency

Ischemic Heart Disease. MYOCARDIAL INFARCTION *The characteristic change in the kinetocardiogram as the result of a myocardial infarction is the presence of a paradoxic systolic outward movement* (POM) [Fig 3-20(2)A] The POM usually begins early in systole (before ejection begins or at the same time) However, in patients with precordial pain, which will be discussed subsequently, the paradoxic pulsation often begins in late systole (late-systolic paradoxic outward movement). The paradoxic outward movements may be classified according to both the time in the cardiac cycle when they begin, and their duration above the baseline as measured on the baseline [Table 3-2(8)]

TABLE 3-2(8). CLASSIFICATION OF SYSTOLIC PARADOXIC OUTWARD MOVEMENTS (POM) DUE TO ISCHEMIC HEART DISEASE

Characteristics	*Early*	*Late*
Onset	Between Q and beginning of ejection	Between onset of ejection and before end of systole
Duration:		
Grade I POM	0 00–0 14 sec	0 00–0 14 sec
Grade II POM	0 15–0 19 sec	0 15–0 19 sec
Grade III POM	0 20⁺ sec (or early systolic *bulge*)	0 20⁺ sec (or late systolic *bulge*)

Table 3-2(9) presents the incidence of paradoxic outward movements in 102 patients with both acute and old myocardial infarction Note that bulges (duration of 0 20 sec or longer) were present in 68 per cent of the patients The location of the POM with the maximal amplitude is of some significance, particularly in differentiating the POM due to myocardial infarction from those of left or right ventricular strain. Table 3-2(10) presents the location of the maximal POM in 69 patients.

As previously stated, the kinetocardiographic tracings cannot be used alone (except in isolated instances) in making a diagnosis. The findings must be considered along with other clinical and laboratory data in order to arrive at a reasonable conclusion Nevertheless, instances are encountered where the kinetocardiographic tracings are of significant clinical

TABLE 3-2(9) INCIDENCE OF BULGES DUE TO MYOCARDIAL INFARCTION

Condition and no of patients	*Bulges, Class III POM* *		*Abnormal movements, Class I and II POM*		*Normal records*	
	No	*Per cent*	*No*	*Per cent*	*No*	*Per cent*
Acute anterior myocardial infarctions, 36	29	81	2	6	5	13
Acute posterior myocardial infarctions, 24	13	62	2	8	9	30
[illegible]	12	57	5	24	4	19
	15	71	0	0	6	29
	42	70	4	7	14	23
	27	64	5	12	10	24
	41	72	7	12	9	16
	28	62	2	4	15	33
	69	68	9	9	24	23

* Paradoxic outward movements

TABLE 3-2(12) INCIDENCE OF PARADOXIC OUTWARD MOVEMENT (POM) IN PATIENTS WITH ELECTROCARDIOGRAPHIC CONDUCTION DEFECTS

Lesion, with no. of patients	Ischemic heart disease				Idiopathic†				Idiopathic CHF, HCVD ‡				Miscellaneous	Total bulge class III POMS
	Total	Normal	Abnormal* movement class I and II POMS	Bulge, class III POMS	Total	Normal	Abnormal* movement, class I and II POMS	Bulge, class III POMS	Total	Normal	Abnormal* movement, class I and II POMS	Bulge, class III POMS		
RBBB, 25	12	1	5	6	7	5	1	1	2	1	0	1	4	12
LBBB, 13	7	0	2	5	3	1	0	2	3	0	1	2	0	8
IVCD, 13	6	1	0	5	0	0	0	0	5	0	0	5	1	11
Total, 51	25	2	7	16	10	6	1	3	10	1	1	8	6	32 §

* An abnormal movement is defined as an outward deflection 0.09–0.19 sec in duration on the base line (class I and II POMS), a bulge is 0.20 sec or longer (class III POMS).

† No history or objective evidence of clinical heart disease

‡ This group includes those patients with hypertensive cardiovascular disease (HCVD) and those with idiopathic congestive heart failure (CHF)

§ This includes four instances of movements labeled as bulges which are probably due in fact to right ventricular stress (patients with mitral valve disease and interatrial septal defects)

Note: RBBB, right bundle branch block, LBBB, left bundle branch block, IVCD, other interventricular condition defects

the atrial movements [Fig. 3-20(2)C]. In addition, left ventricular thrust may decrease in amplitude during decompensation and subsequently increase on digitalization. A plot of the ratio obtained by dividing the total amplitude of the tracing into the amplitude of the atrial movement (K_1 tracing) during digitalization reveals a marked reduction in the ratio as compensation is achieved. However, the ratio may become larger as digitalis toxicity is neared. This may be of help in following patients during digitalization. Normally, the atrial amplitude is not over one-third of the total amplitude of the tracing; however, during cardiac decompensation, the atrial movements may be the largest movements in the tracings.

An increase in amplitude of the atrial movements may occur in some patients in the absence of heart failure. For example, patients with uncomplicated mitral stenosis or tricuspid valvular lesions have a very large atrial movement without signs of overt congestive heart failure.

TIMING OF CARDIAC EVENTS

The apex cardiograms have been used by various investigators to time certain heart sounds (Lewis and Dock; Kuo et al. (1957), Dock et al.), and recent investigators have reemphasized their value (Benchimol et al., Jeffries). For example, an opening snap may be easily identified by its relationship to the onset of the ventricular filling movement. Similarly, a protodiastolic gallop and a physiologic 3d heart sound may be identified by their occurrence near the peak of the filling movement. In addition, an atrial (or presystolic) gallop occurs close to the peak of the atrial movements.

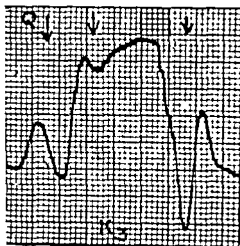
SUMMARY

The kinetocardiogram does offer useful information, but the findings must be correlated with other clinical data for proper interpretation. At the present time the kinetocardiographic tracings are of some use clinically in the following situations:

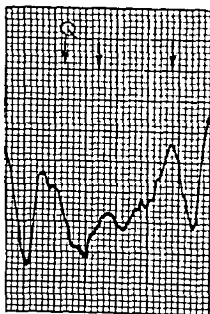
1. It is probably the best means available for detecting abnormalities of right ventricular function, except in patients with congenital heart disease (undefined as yet).

2. A higher percentage of abnormality occurs in patients with arterial diastolic hypertension and aortic valvular disease than is noted either in the electrocardiogram or from standard heart-size measurements (using 6-ft chest teleoroentgenograms).

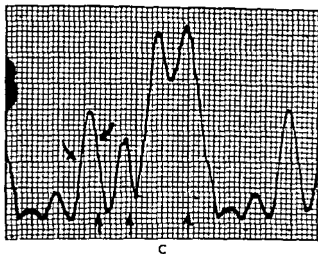
3. The tracings may be particularly useful in patients with ischemic heart disease, as a POM or bulge in a patient with suspected myocardial infarction may offer sufficient evidence to substantiate the suspected clinical diagnosis. In fact, a bulge may be present very early in the course of the infarction, before other clinical evidence becomes manifested. A paradoxic pulsation or bulge may be sufficient



A



B



C

Fig. 3-20(2). A. Record taken from the K_3 point in a patient with an acute myocardial infarction to illustrate the marked paradoxic pulsation (bulge) that often occurs as a result of the noncontracting ischemic area of the myocardium The time lines are 0 02 sec apart. The arrow labeled Q indicates the QRS complex of the electrocardiogram, second arrow, the upstroke of the carotid pulse; third arrow, the carotid incisural notch. Note the marked outward movement during systole. Duration of the base line is 0 41 sec; it can therefore be classified as a grade III POM or true bulge. B Prominent late-systolic paradoxic outward movement which may occur in patients with angina pectoris. Time lines are 0 02 sec apart. The arrow labeled Q indicates the onset of the QRS complex in the electrocardiogram; second arrow, onset of ejection as determined by the upstroke of the carotid pulse, third arrow, the carotid incisural notch Note that the late-systolic movement begins about 0 08 sec after the second arrow, reaching a peak at the time of the carotid incisural notch C. An example of the marked exaggeration of the atrial movements that can occur in patients with congestive heart failure. The first arrow at the bottom of the record indicates the onset of the QRS complex in the electrocardiogram, second arrow, the upstroke in the carotid pulse, third arrow, the carotid incisural notch. The time lines are 0 02 sec apart The curve arrows point to the atrial movements. Since the atrial upstroke (first curved arrow) is 20 mm and the total amplitude of the complex is approximately 37 mm, the ratio obtained by dividing the total amplitude into the amplitude of the atrial movement is 0 54 (normal is rarely over 0 33)

large fraction of the patients with episodes of precordial pain develop a significant POM on exercising.

ELECTROCARDIOGRAPHIC CONDUCTION DEFECTS. Patients with electrocardiographic defects often have a POM. When such movements occur, particularly in *left bundle branch block*, they probably indicate a myocardial infarction (age undetermined). Table 3-2(12) gives the incidence of bulges occurring in a group of 51 patients with electrocardiographic conduction defects. A normal kinetocardiogram from a patient with electrocardiographic conduction defects, along with no other clinical evidence of heart disease, may be taken as evidence that the conduction defect is of no clinical significance, particularly in a patient with right bundle branch block. However, a POM (bulge) in patients with left bundle branch block should be seriously considered as indicating an underlying myocardial infarction.

Heart Failure. Patients with heart failure may show an increase in the amplitude of

TABLE 3-2(12) INCIDENCE OF PARADOXIC OUTWARD MOVEMENT (POM) IN PATIENTS WITH ELECTROCARDIOGRAPHIC CONDUCTION DEFECTS

Lesion, with no. of patients	Ischemic heart disease				Idiopathic †				Idiopathic CHF, HCVD ‡				Miscellaneous	Total bulge, class III POMS
	Total	Normal	Abnormal * movement, class I and II POMS	Bulge, class III POMS	Total	Normal	Abnormal * movement class I and II POMS	Bulge, class III POMS	Total	Normal	Abnormal * movement, class I and II POMS	Bulge, class III POMS		
RBBB, 25	12	1	5	6	7	5	1	1	2	1	0	1	4	12
LBBB, 13	7	0	2	5	3	1	0	2	3	0	1	2	0	9
IVCD 13	6	1	0	5	0	0	0	0	5	0	0	5	1	11
Total, 51	25	2	7	16	10	6	1	3	10	1	1	8	6	32 §

* An abnormal movement is defined as an outward deflection 0 09–0 19 sec in duration on the base line (class I and II POMS), a bulge is 0 20 sec or longer (class III POMS).

[illegible]

disease [illegible]

Note RBBB right bundle branch block, LBBB, left bundle branch block, IVCD, other interventricular condition defects

the atrial movements [Fig 3-20(2)C] In addition, left ventricular thrust may decrease in amplitude during decompensation and subsequently increase on digitalization A plot of the ratio obtained by dividing the total amplitude of the tracing into the amplitude of the atrial movement (K_1 tracing) during digitalization reveals a marked reduction in the ratio as compensation is achieved. However, the ratio may become larger as digitalis toxicity is neared. This may be of help in following patients during digitalization. Normally, the atrial amplitude is not over one-third of the total amplitude of the tracing; however, during cardiac decompensation, the atrial movements may be the largest movements in the tracings.

An increase in amplitude of the atrial movements may occur in some patients in the absence of heart failure For example, patients with uncomplicated mitral stenosis or tricuspid valvular lesions have a very large atrial movement without signs of overt congestive heart failure.

TIMING OF CARDIAC EVENTS

The apex cardiograms have been used by various investigators to time certain heart sounds (Lewis and Dock; Kuo et al (1957), Dock et al), and recent investigators have reemphasized their value (Benchimol et al , Jeffries). For example, an opening *snap* may be easily identified by its relationship to the onset of the ventricular filling movement. Similarly, a *protodiastolic gallop* and a *physiologic 3d heart sound* may be identified by their occurrence near the peak of the filling movement. In addition, an atrial (or presystolic) gallop occurs close to the peak of the atrial movements

SUMMARY

The kinetocardiogram does offer useful information, but the findings must be correlated with other clinical data for proper interpretation At the present time the kinetocardiographic tracings are of some use clinically in the following situations.

1. It is probably the best means available for detecting abnormalities of right ventricular function, except in patients with congenital heart disease (undefined as yet)

2. A higher percentage of abnormality occurs in patients with arterial diastolic hypertension and aortic valvular disease than is noted either in the electrocardiogram or from standard heart-size measurements (using 6-ft chest teleoroentgenograms).

3 The tracings may be particularly useful in patients with ischemic heart disease, as a POM or bulge in a patient with suspected myocardial infarction may offer sufficient evidence to substantiate the suspected clinical diagnosis. In fact, a bulge may be present very early in the course of the infarction, before other clinical evidence becomes manifested A paradoxic pulsation or bulge may be sufficient

evidence to establish the diagnosis of ischemic heart disease in patients with atypical forms of angina pectoris.

4 A bulge in patients with interventricular conduction defects (excluding those instances of right bundle branch block where the outward movement is obviously due to right ventricular hypertrophy) offers evidence that the underlying myocardial process is ischemic heart disease.

5 The kinetocardiogram may be valuable in following patients with interatrial defects or with mitral stenosis Serial records over a period of months or years will often furnish indirect evidence of increasing pulmonary vascular resistance and thus avoid the necessity for repeated catheterization of the right heart. However, when the crucial decision as regards operation is to be made, this indirect evidence should be substantiated by more direct measurements. Similarly, in the postoperative phase, the kinetocardiogram will give an important clue as to the success of the procedure by demonstrating indirect evidence, which may appear as early as 10 days after surgical procedure, of reduced pulmonary vascular resistance

6 An increase in atrial movements may often offer some confirmatory evidence of congestive heart failure when the clinical manifestations may be equivocal. In addition, the amplitude of the atrial movements divided by the total amplitude of the tracing may offer an objective approach in following patients during digitalization.

7. The kinetocardiographic tracings aid in defining the time in the cardiac cycle of certain cardiovascular sounds, such as the opening snap and the various types of diastolic gallops

THE ACCELEROGRAM OF THE PRECORDIUM

INTRODUCTION

The study of the pulse and of the heart beat challenged medicine for many centuries Harvey's superb description of the ever-changing aspect of the exposed heart and of the complexity of its movements dramatically pictures the elusiveness of this process to direct observation. Repeated attempts of physiologists of the nineteenth century, an era so rich in physiologic achievements, failed to provide exact instrumental standards for the study of the heart beat The mechanical aspects, even today, are less well understood than the electrical manifestations of the heart.

Pulsatory movements and forces are influenced by numerous factors. Structural and biochemical properties of the heart and the blood, blood volume, pressures and resistances, neurohumoral regulations, and extracardiovascular *structures play important roles in causing or* modifying the pulsatory movements within and outside the heart Just as the study of single factors encounters numerous problems, so also does the analysis of the resulting complex pulsation

A task yet to be solved is the measurement of magnitude, spread, attenuation, and transmission of the forces created by ventricular systole Kinetic forces are responsible for pulsations Pulse waves and recoil forces are superimposed on blood flow and, with simultaneous pressure-volume changes, result in rhythmic movements (vibrations) of vessels, organs, precordium, etc These vibrations are transmitted to the whole body and consist of low and high oscillatory frequencies. Definite frequency bands of these vibrations have to be studied with definite instrumental techniques.

Precordial oscillations include "high-frequency" vibrations, commonly referred to as "heart sounds." Heart sounds are just one aspect of the vibrations produced by the kinetic energy of the heart

Systolic forces account for the displacement of stroke volume into the vessels. Simultaneously, a displacement of the precordium (apical thrust) and of the total body mass (ballistocardiogram) can be sensed Any *displacement* occurs with a given *velocity* and *acceleration*, each being accessible to instrumental perception.

Table 3-2(13) lists methods in current use to record various aspects of pulse and heart beat No single graphic method supplies complete information on the mechanical efficiency or reserve of the heart Even those aspects of the heart beat that are accessible to exact measurement require exacting procedures For this reason, researchers have been more and more attracted by the relatively simpler methods, like ultra-low-frequency ballistocardiography, kinetocardiography, and precordial accelerography

TABLE 3-2(13). A SURVEY OF SOME CLINICAL AND EXPERIMENTAL GRAPHIC METHODS OF RECORDING PULSATORY PHENOMENA

Method	*Registered phenomena*
ECG	Electrical phenomena
Phonocardiography	Displacement or acceleration of precordial pulsation (frequency range. c. 30–1,000 cps)
Manometry	Intracardiac, intravascular, intrathoracic pressures
Jugular, carotid, femoral, etc., pulse tracings	Volume or pressure changes in veins and arteries
Plethysmography	Volume or pressure changes in veins and arteries
Electrokymography	Displacement of contours (heart or vessels)
Kinetocardiography, apex cardiography, "low-frequency" tracings	Displacement or velocity of precordial pulsation (probable frequency range: c. 2–50 cps)
Ballistocardiography	Pulsatory displacement, velocity, or acceleration of the body (frequency range: c. 2–30 cps)
Precordial accelerography	Acceleration of precordial pulsation (frequency range: c. 2–30 cps)
Rheocardiography, impedance plethysmography	Electrical impedance due to pulsatory changes in blood content

TABLE 3-2(14). MODERN PRECORDIAL METHODS AND STUDIES

Author(s)	*Year*	*Studies and methods*
Atzler and Lehmann	1932	Dielectrography (volume changes of the heart?)
Schütz	1933	Apex cardiogram [illegible]
Dalbecco and Palomba	1937	[illegible]
Rosa	1939	[illegible]
Landes	1940	[illegible]
Smith, Kountz, et al	1940–1944	[illegible]
Rosa	1944	[illegible]
Foulger, Smith, and Fleming	1947	[illegible]
Johnston and Overy	1951	[illegible]
Luisada and Magri	1952	[illegible] ... and epigastrium
Harrison, Eddleman, Reeves, Wilhs, et al	1953–1958	Kinetocardiography
Schuman, Lilson, *et al*	*1954*	Thoracic ballistocardiography
Kazmeier and Schild	*1955*	*Thoracic ballistocardiography*
Groom and Boone	1956	Heart sounds and vibrations
Rosa and Kunos	*1956*	Comparison of precord[illegible]
Eddleman	1958	K[illegible]
Mounsey	1957–1959	Pr[illegible]
Eddleman, Tucker, Knowles, *and Eddleman*	1955–1957	*Kinetocardiography* in mitral and aortic insufficiency
Agress, Fields, Muller, and Wegner	1959–1961	Analysis of heart vibrations in hypoxia and *coronary heart* disease
Rosa	1958	Ballistic cardiography. Accelerographic studies *in* 1,958 patients with cardiac disease *Studies in experimental* streptococcal carditis
Hollis, Hollis and Vetrone	1958–1959	Precordial forces and electromechanical events *of cardiac* contraction
Rosa and Luisada	*1959*	Tachog[illegible]
Eddleman, et al	*1959*	
Rosa and Kaplan	1960	
Skinner et al	1961	
Schneider and Kuzkaze	1961	
Coghlan, *Prieto,* and Harrison	1961	

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A task yet to be solved is the measurement of magnitude, spread, attenuation, and transmission of the forces created by ventricular systole. Kinetic forces are responsible for pulsations. Pulse waves and recoil forces are superimposed on blood flow and, with simultaneous pressure-volume changes, result in rhythmic movements (vibrations) of vessels, organs, precordium, etc. These vibrations are transmitted to the whole body and consist of low and high oscillatory frequencies. Definite frequency bands of these vibrations have to be studied with definite instrumental techniques.

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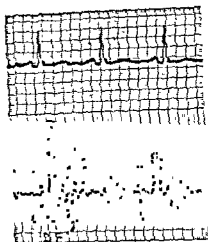


Fig. 3-20(3). Normal precordial acceleration tracing (PACT). Forty-four-year-old woman with episodes of precordial pain and hypertension. ECG: ST-T changes. Accelerographic analysis I-I' complex within normal limits

3. Accelerograms taken from the surface of a plaster cast dressing on surgical patients with extended costal fractures show the customary form of precordial tracing. The *precordial accelerogram* has the pulsatory acceleration pattern of the *total thoracic mass*.

Few studies have been made to evaluate interactions between receiver and body *surface* (von Gierke, Franke).

To study possible artefacts caused by the mode of *attachment* of the receiver, an inflatable *pneumatic cuff* can be substituted for rubber *straps* to hold the receiver. No distortion of the tracing takes place when a pressure of 20 mm Hg or less is applied. At pressure levels *above 20 mm Hg* the tracings show increasing distortion. The weight of the receiver can be increased up to 350 Gm without change in oscillatory pattern.

Precordial Displacement and Precordial Acceleration. Pulsatory motions are generally visible as "*displacements*" of the pulsating area. Landes first showed that the so-called "apical cardiogram" is a displacement tracing.

The following are the mathematic *correlations* between pulsation (displacement) and acceleration.

1. Pulsatory displacement (pulsation) = $D = a \sin \omega t$, where a = amplitude of largest oscillation at time t, ω = oscillatory frequency 2π/sec.

2. Pulsatory acceleration = $A = -a\omega^2 \sin \omega t$.

Acceleration is the second mathematic derivative of displacement. As in the electrocardiogram, displacement and acceleration are graphically best represented as time functions. The tracings show a time sequence of peak values of displacement or acceleration. The PACT can be derived from the displacement cardiogram and vice versa. Instrumental computers allow for the simultaneous recording of both tracings, because displacement and acceleration are two aspects of the same movement. The acceleration tracing is richer in details and less subject to distortion by respiratory movements than the displacement tracing. The former can be explained by the fact that during ventricular isometric tension, contractile forces prevail on movements (Ernsthausen), and motions lag behind forces driving the body (Deuchar et al.). The acceleration tracing reflects forces rather than mo- [illegible] is generally absent in [illegible] on [illegible] nd the constancy of the acceleration tracing seem to be superior to those of the displacement tracing.

Precordial Acceleration Tracing (PACT) and Phonocardiogram. Like the acceleration tracing, a phonocardiogram can be derived from the apical cardiogram. This can be done either mathematically (Fourier analysis) or *instrumentally*, by application of frequency filters. The phonocardiogram is a differentiated apical cardiogram. Sound frequencies have been derived from the plethysmogram by Landes and from the BCG by Edson.

Landes (1940) was the first to show that the PACT is similar to the linear *low-frequency* phonocardiogram. Rappaport and Sprague (1942) also noticed the resemblance between phonocardiogram and low-frequency *precordial* tracings and *considered the linear* phonocardiogram an apical cardiogram. Dunn and Rahm (1952 and 1953) devised a *low-frequency crystal* microphone (electrostethograph) *for* the study of the precordial *transmission* of cardiodynamics. Schütz, Dieter, and Rosa (1959) made a direct *comparison* between the low-frequency phonocardiogram and the PACT.

There is a resemblance between the *accelerogram* and the *low-frequency* phonocardiogram. This is because heart-sound microphones often pick up vibrations of the chest wall *below* the auditory level (15 to 20 *cps*). "Low-frequency" phonocardiograms, however, are not *identical* with precordial accelerograms. Most microphones used in *routine* phonocardiography do not have a *linear response* for frequencies below 20 *cps*. Therefore, the ampli-

A lack of agreement on standardization accounts for differences in the pattern of various ballistic graphs. Opinions on the practical value of displacement, velocity, or acceleration pickups are as yet divided. Moreover, some of the graphs published in the literature seem to represent transitional patterns. Table 3-2(14) contains a short chronologic survey of *studies on precordial pulsatory vibrations.* The present chapter deals with the theoretic and clinical aspects of *precordial accelerography.*

THE PHYSIOLOGIC AND PHYSICAL BASIS OF PRECORDIAL PULSATIONS

Pulsation is a resultant of *constituent vectors.* The primary cause of pulsation is the *contraction of the heart* which displaces blood (stroke volume) from the ventricles into the systemic and pulmonary vessels. The amplitude of ballistocardiographic deflections is proportional to the *stroke volume* (Starr, Nickerson) and is modified by various factors, including *peripheral resistance* (Landes and Kummer). It may be assumed that the same holds true for precordial pulsations. The amplitude of the latter decreases with *blood loss,* but increases in *hemorrhagic shock* (Rosa, MacCanon, and Inoue). Systolic-diastolic changes in the *position of the heart* (torsion, rotation) and the anatomic build of the vascular tree (aorta) contribute to the formation of additional component vectors. Pulsatory forces originated within the four cardiac chambers may reciprocally and vectorially influence each other (Frederick and Eddleman). A considerable amount of the cardiac contractile energy is neutralized, modified, or cancelled before reaching the body surface (Reeves et al.). Recoil forces (Newton's law) and rebound waves play a considerable role in this modifying process.

Many of the physiologic parameters involved are subject to nervous, humoral, and respiratory influences.

The resulting *pulsatory pattern* depends on the *oscillatory frequency* of the vibrating mass (body, thorax, etc.), which is determined by (1) velocity of blood flow, (2) flow volume, and (3) peripheral resistance. The velocity of blood flow is proportional to pressure. It is, therefore, most likely that the resulting precordial oscillatory pattern depends on the interplay of pressures within the cardiac chambers, great vessels, and thorax. The resulting oscillatory pattern may be distorted by instrumental artifacts or changes in cardiovascular function, like those caused by experimental application of drugs (Rosa and Kaplan; Harrison et al., 1961) or disease.

"Distortion of the BCG may be due to variation in the frequency of the impressed force, *the circulatory apparatus, the natural frequency* of the vibrating mechanical mass, the body, or the frequency response of the transducer-filter-oscillograph" (Frederick and Eddleman). A similar distortion might be considered for the precordial tracings.

It is hard to locate the source and magnitude of the vibrational energy because the heart cannot be vectorially separated from the totality of the vibrating body, which includes the blood mass and the vascular tree. In precordial accelerography, standards concerning the physical properties of the thorax (mass, impedance, elasticity, resonance, reactance, etc.) have to be established to facilitate the quantitative measurement of the energy transmitted from the "source" to the precordial surface.

In the present stage of knowledge, it is preferable to consider the precordial forces as *resulting vectors, acting mainly in the posteroanterior axis of the thorax.* Notwithstanding allowances for resonance vibrations and attenuation by intermediate thoracic structures, the shape of the precordial acceleration tracing (PACT) offers a reproducible standard for comparative studies [Fig. 3-20(3)]. Time sequence, frequency pattern, and relative amplitude of the consecutive oscillations reveal a pattern equivalent to the second derivative of *the pressure curve (within the pulmonary* artery and the aorta) and also to that of the ultra-low-frequency acceleration ballistocardiograph (BCG). The time relationship of accelerographic to electrocardiographic and other cardiovascular tracings proves that precordial vibrations stem from mechanical events of the cardiac cycle. Experimental attempts to determine some *qualitative* aspects of the *transmission* of intrathoracic pulsatory forces to the precordium disclosed that

1. The *precordial* pattern of acceleration is similar to that found over the left ventricular surface of the dog.

2. The pattern of the second time derivative of *pressure in the pulmonary artery* of the dog is identical with that of precordial acceleration

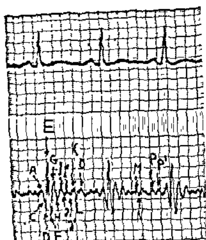


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tude of ultra-low-frequency oscillations may be misrepresented. Only heart-sound microphones with a frequency response proportional to ω^2 to ω^3 should be used in accelerography. An adequate frequency response for frequencies as low as 2 cps is desirable. In the 5 to 25 cps range, both precordial displacement and PACT resemble the low-frequency phonocardiogram.

Precordial Tracings and Ballistocardiograms. Landes (1940) demonstrated a similarity between the pattern of longitudinal precordial acceleration and that of the head-foot BCG.

The concept that ballistic pulsatory forces contribute to precordial vibrations was advocated by many investigators (Kuo et al., 1952, Edson et al., Burch et al., Eddleman et al., 1953, Harrison et al., 1953, Talbot and Harrison, 1955, Ernsthausen, Reeves et al., Merlen and Desruelles, Nyboer and Watson, etc.).

Landes believed that the "ideal cardiogram" represents the algebraic sum of venous return to and arterial outflow from the thorax. Recent studies of Noordergraaf on the displacement of the center of gravity support this idea. The ultra-low-frequency BCG is actually the "ideal cardiogram" of Landes.

A similarity of ultra-low-frequency *precordial tracings* to ultra-low-frequency *ballistocardiograms* (Rosa and Luisada) is also illustrated by BCG tracings published by Hollis (1956), Elliott, Packard, and Kyrazis, and Deuchar, Talbot, and Scarborough.

The mechanism causing ballistic motions is probably similar to that causing precordial pulsations. The physical meaning of the BCG, however, is different from that of precordial tracing. The BCG represents longitudinal forces driving the *whole body*, while the precordial forces recorded by the accelerogram act in the anteroposterior axis of the *thorax*. Artefacts due to the inertia of limbs (Honig and Tenney), abdominal organs, and differences in extracardiovascular structures are probably reduced by the precordial approach. The shape of the PACT is less affected by respiration than that of the BCG and is not dependent on the mode of attachment of the body to the supporting platform. In precordial accelerography, the structure of the supporting platform has no influence on the shape of the tracing. Neither precordial nor ballistocardiographic methods allow the measurement of the absolute magnitude of cardiovascular forces, because the rate of transmission from center to body surface is unknown. The two methods, therefore, are not competitive but should complete each other in the study of the heart beat.

TECHNIQUE

The tracings are taken with the patient in a supine or semirecumbent position either in his bed or on the table for routine electrocardiography. The pickup,[1] which is similar to a heart-sound microphone, is placed on the bare skin with its center over the fifth rib, 1 or 2 cm to the left of the sternum. Tracings taken from intercostal spaces may appear as mirror images.

The output voltage of the electromagnetic pickup varies with the impedance of the surface, whose vibrations are registered. Records taken over soft tissues (carotid area, epigastrium, intercostal spaces) may represent tracings of velocity instead of acceleration.

Different regions of the thoracic wall were studied in order to investigate the differences between the various vibratory patterns. The multitude of the recorded patterns and the large number of variants induced the author to standardize the location of the pickup. All tracings published in this chapter were taken with the pickup attached to the input of the d-c amplifier (model 60-200, serial 668) of a Twin-Viso Sanborn Direct Writer Electrocardiograph (model 60.1300 B, serial 9), with a film speed of 50 mm/sec. Proper contact between precordium and pickup can be secured by the application of a rubber strap or of a metal plate (weight, 350 Gm, size, 10 by 10 cm) placed over the receiver.

In normal subjects, with quiet respiration, there are only minor variations in amplitude and pattern of the tracing [Fig. 3-20(3)]. On the other hand, large respiratory variations may occur in patients with cardiac disease [Fig. 3-20(9)]. In order not to miss this type of valuable information, tracings should be taken during quiet respiration. Dyspnea does not exclude the examination. The graphic pattern of the early-systolic events may be best visualized in expiratory apnea. It is convenient to take the record simultaneously with a routine electrocardiogram in lead 1 or 2 for time reference. Serious mistakes could take place in the interpretation of the tracing without the guidance of the electrocardiogram.

[1] Accelerometer, manufactured by the F and G Sound Installation Co., Chicago, Ill.

Differences in deflection time, time constant, and frequency response of some electrocardiographs may necessitate the use of a standardized filter band (2 to 25 cps) for recording the PACT. The natural frequency of most direct-writer electrocardiographs matches the requirements without need for filtration.

The sensitivity of the amplifier should be set so that the amplitude of the largest midsystolic deflection is about 25 to 30 mm and the two end-systolic deflections are about 3 to 5 mm

THE PATTERN OF THE NORMAL PRECORDIAL ACCELERATION TRACING (PACT)

The first technically correct PACT was probably the apex cardiogram published by Schütz (1933) The "ideal" cardiogram of Landes (1940) is the mathematic and physical basis for the study of the pattern of the PACT. This was reproduced by Landes, Rosa, Mounsey, Hollis, and Hollis and Vidrine, in more than 7,000 cases

The tracing [Fig 3-20(3)] has no intrinsic *base line* An imaginary base line may be established by connecting the J *troughs of two* consecutive cycles. In some patients *with a slow* heart rate [Fig 3-20(4)], a relatively *quiet* base line in diastole may be recognized, with vibrations usually not *descending below the* "base line"

The consecutive oscillations of the PACT represent peak values of acceleration and *deceleration* during the pulsatory cycle. Acceleration takes place during the rise of an oscillation; deceleration is expressed by the descending limb of the deflection The "regular" pattern in normal human subjects, as well as in the dog and rabbit, includes a *characteristic* relationship between the amplitudes of consecutive oscillations The registered amplitude of oscillations depends upon the selected sensitivity of the amplifier, *the amplitude pattern* refers to the *relative* amplitude of consecutive individual deflections, in conformity with empirical and experimental findings and theoretic requirements

Each peak and each trough is labeled by a capital letter *in* alphabetic and chronologic order

Peaks in systole A, C, E, G, I, K
Troughs in systole. B, D, F, H, J

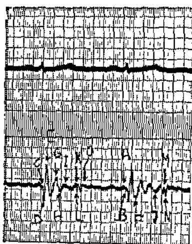


Fig. 3-20(4). Normal PACT. Fifty-two-year-old male with episodes of precordial pain ECG normal tracing

Peaks in diastole· M, O, P
Troughs in diastole: L, N

Systole. The tracing is dominated by a tall E peak *The second tallest peak is* G. A and I have nearly equal amplitudes.

The amplitude of A is larger than that of C. C may appear as a notch on the descending A-D *segment.* E is the tallest peak of the normal tracing. The amplitudes decrease from E to K. G is taller than I. The height of K may vary The deepest trough of the tracing is *usually D* [Fig. 3-20(4)]. More studies are needed to *clarify* whether an F deeper than D [as in Fig 3-20(3)] should be interpreted as an *abnormal* pattern The foregoing *observations* help to recognize an occasional mirror-image *pattern.* Slight variations in shape and amplitude of oscillations in *consecutive cycles,* as seen in Fig. 3-20(3), are due to the effect of *respiration on* hemodynamics

The amplitude of D and E is largest in inspiratory apnea; that of A-B-C, in expiratory apnea.

Diastole. K-L is a rapid, downward deflection The *depth of* L varies Normally L does not descend deeper than *D or F.* The normal amplitude of O is smaller than that of K. P *and* P' *do not* rise higher than A and do not descend deeper than J

No oscillation taller *than* O appears normally in mid-diastole.

The Number of Oscillations. The PACT of young, healthy subjects consists of smooth,

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The concept that ballistic pulsatory forces contribute to precordial vibrations was advocated by many investigators (Kuo et al., 1952, Edson et al, Burch et al, Eddleman et al., 1953, Harrison et al., 1953; Talbot and Harrison, 1955; Ernsthausen; Reeves et al., Merlen and Desruelles, Nyboer and Watson, etc.).

Landes believed that the "ideal cardiogram" represents the algebraic sum of venous return to and arterial outflow from the thorax Recent studies of Noordergraaf on the displacement of the center of gravity support this idea The ultra-low-frequency BCG is actually the "ideal cardiogram" of Landes.

A similarity of ultra-low-frequency *precordial tracings* to ultra-low-frequency *ballistocardiograms* (Rosa and Luisada) is also illustrated by BCG tracings published by Hollis (1956), Elliott, Packard, and Kyrazis, and Deuchar, Talbot, and Scarborough

The mechanism causing ballistic motions is probably similar to that causing precordial pulsations The physical meaning of the BCG, however, is different from that of precordial tracing The BCG represents longitudinal forces driving the *whole body*, while the precordial forces recorded by the accelerogram act in the anteroposterior axis of the *thorax* Artefacts due to the inertia of limbs (Honig and Tenney), abdominal organs, and differences in extracardiovascular structures are probably reduced by the precordial approach. The shape of the PACT is less affected by respiration than that of the BCG and is not dependent on the mode of attachment of the body to the supporting platform. In precordial accelerography, the structure of the supporting platform has no influence on the shape of the tracing. Neither precordial nor ballistocardiographic methods allow the measurement of the absolute magnitude of cardiovascular forces, because the rate of transmission from center to body surface is unknown. The two methods, therefore, are not competitive but should complete each other in the study of the heart beat.

TECHNIQUE

The tracings are taken with the patient in a supine or semirecumbent position either in his bed or on the table for routine electrocardiography. The pickup,[1] which is similar to a heart-sound microphone, is placed on the bare skin with its center over the fifth rib, 1 or 2 cm to the left of the sternum. Tracings taken from intercostal spaces may appear as mirror images

The output voltage of the electromagnetic pickup varies with the impedance of the surface, *whose vibrations are registered.* Records taken over soft tissues (carotid area, epigastrium, intercostal spaces) may represent tracings of velocity instead of acceleration.

Different regions of the thoracic wall were studied in order to investigate the differences between the various vibratory patterns. The multitude of the recorded patterns and the large number of variants induced the author to standardize the location of the pickup All tracings published in this chapter were taken with the pickup attached to the input of the d-c amplifier (model 60-200, serial 668) of a Twin-Viso Sanborn Direct Writer Electrocardiograph (model 60 1300 B, serial 9), with a film speed of 50 mm/sec Proper contact between precordium and pickup can be secured by the application of a rubber strap or of a metal plate (weight, 350 Gm, size, 10 by 10 cm) placed over the receiver.

In normal subjects, with quiet respiration, there are only minor variations in amplitude and pattern of the tracing [Fig 3-20(3)]. On the other hand, large respiratory variations may occur in patients with cardiac disease [Fig 3-20(9)] In order not to miss this type of valuable information, tracings should be taken during quiet respiration Dyspnea does not exclude the examination The graphic pattern of the early-systolic events may be best visualized in expiratory apnea. It is convenient to take the record simultaneously with a routine electrocardiogram in lead 1 or 2 for time reference Serious mistakes could take place in the interpretation of the tracing without the guidance of the electrocardiogram.

[1] Accelerometer, manufactured by the F and G Sound Installation Co, Chicago, Ill

TABLE 3-2(15) TIME COINCIDENCES OF ACCELEROGRAPHIC DEFLECTIONS WITH CARDIOVASCULAR GRAPHS

PACT	ECG	*Phonocardiogram*	*Intracardiac pressures*	*Pulse tracings*	*Tentative interpretation*	*Remarks*
A	Q or R	First slow vibration of 1st heart sound	Slow rise of ventricular pressures	Peak or descending limb of the "a" wave of the jugular phlebogram	Start of ventricular isometric contraction	
A-C	Initial 0.04 sec of QR	Slow vibrations of 1st heart sound			Right ventricular isometric contraction period	Force of predominantly muscular origin?
C	Summit of R to S-ST junction	First rapid vibration of 1st hea sound				
E	S-T segment	Ejection sound aortic opening				
				gram	tricular ejection	
A-E					Left ventricular isometric tension period	
G	Rise of the T wave	End of 1st heart *sound*	First peak of ventricular pressures	Anacrotic shoulder of carotid *tracing* Rise of abdominal aortic tracing		Force of predominantly vascular origin?
C-G	S-T segment			H-I-J area of the ballistocardiogram	Rapid right ventricular ejection	Correlations of oscillatory amplitude with stroke volume are under study
E-G					Rapid left ventricular ejection	
I	Summit of T wave		Plateau, intersystolic dip, or second peak of pressure tracing			Coincidence with summit of T wave ±0.04 sec
G-K	T wave				Reduced ventricular ejection	
K	End of T wave	Aortic component of the 2d heart sound		Carotid incisura	End of mechanical systole, aortic closure	Coincidence with the end of the T wave, ±0.04 sec
K'		Pulmonic component of 2d heart sound			Pulmonic closure	
M					Tricuspid opening	
N		Opening snap			Mitral opening	
O		3d heart sound		Peak of the "v" wave of the jugular phlebogram	Rapid ventricular filling	
P	Peak or descending limb of P	4th heart sound			Atrial contraction (dynamic phase)	0.02-0.04 sec after the onset of P wave, 0.10-0.12 sec before Q wave
P'	P-R interval	4th heart sound			Atrial outflow	

4. Early diastole. K-O interval.

5. Mid- and late diastole (presystole). P-A interval.

Table 3-2(15) shows the time coincidence of the various deflections with the cardiovascular events. (It should be kept in mind that time coincidence does not necessarily express causal relationship.)

Deviations from the usual onset time of the individual oscillations are best detected by a comparison with the simultaneous electrocardiogram.

THE CRITERIA OF THE ABNORMAL PACT

Amplitude criteria:

1. Rise of P above A [Fig. 3-20(10)].
2. Descent of P-A belo...
3.
4.
5.
6.
7. Decrease of E below the amplitude of G and I [Fig. 3-20(15)].

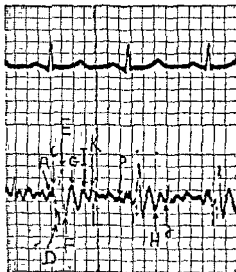


Fig. 3-20(5). PACT with grade 1 abnormality. Sixty-five-year-old woman with coronary heart disease ECG normal tracing Accelerographic analysis midsystolic abnormality; the D-F segment is splintered and consists of a number of high-frequency oscillations

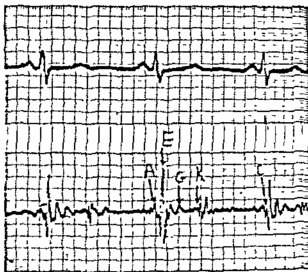


Fig. 3-20(7). PACT with grade 2 abnormality Seventy-seven-year-old woman with coronary heart disease. ECG. rare ventricular premature beats. Accelerographic analysis: midsystolic and end-systolic abnormalities Respiratory variations of the E-G and G-K segment. Peak I is absent.

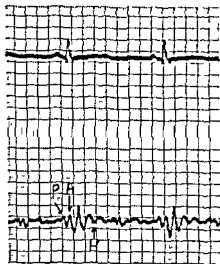


Fig. 3-20(6). PACT with grade 1 abnormality. Eighty-year-old woman with coronary heart disease. ECG: depressed ST in 1–2; inverted T in V3–4. Accelerographic analysis. end-diastolic abnormality The P-A segment is concave and deeper than H and J.

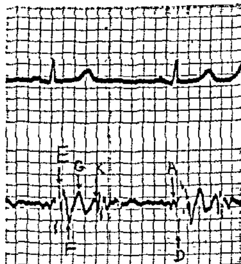


Fig. 3-20(8) PACT with grade 2 abnormalities. Eighty-two-year-old male with episodes of precordial pain due to coronary heart disease ECG. moderate ST depression. Accelerographic analysis midsystolic and end-systolic abnormalities. Numerous high-frequency oscillations between E and F. No I peak

sharp lines. The oscillations are pointed (D, E, F) or rounded (G, H, I, J). An occasional notch may be seen on D-E, E-F [Fig 3-20(6)], F-G, or G-H [Fig. 3-20(8)].

E, G, I, K, and P [I in Fig. 3-20(3), K in Fig. 3-20(5)] may be split (E′, G′, I′, K′, P′). Oscillations consisting of three or more peaks [D-E-F in Fig. 3-20(5)] are considered abnormal.

The *time coincidence* of the accelerographic deflections with various cardiovascular graphs permits the subdivision of the tracing into six phases.

1. Early systole. This consists of the A-B-C segment. The phase starts with A and ends with C.
2. Midsystole: C-G interval
3. End systole: G-K interval

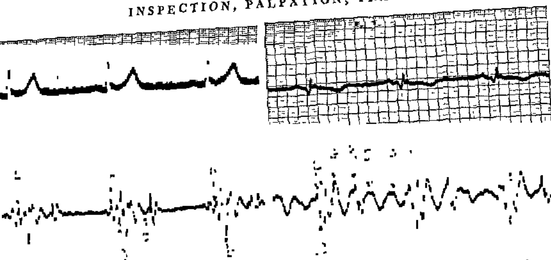


Fig 3-20(11) PACT with grade 3 abnormalities. Thirty-nine-year-old male Recent posterior infarct. Accelerographic analysis early systole—tall C (taller than A), midsystole—high-frequency vibrations between D and F; end diastole—deep P-A segment

Fig. 3-20(13) PACT with grade 5 abnormalities. Sixty-year-old male. Recent anterolateral infarct Accelerographic analysis early systole—tall C (taller than A), midsystole—high-frequency vibrations between D and F, end systole—no I peak, mid-diastole —broad, tall O; end diastole—deep P-A segment.

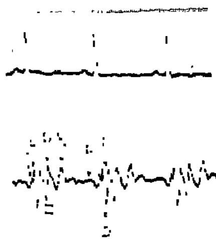


Fig 3-20(12) PACT with grade 4 abnormalities Fifty seven-year-old male Recent anteroseptal infarct Accelerographic analysis early systole—tall C (taller than E), midsystole—high frequency vibrations between D and F, end systole—no I peak, end diastole—deep P-A segment

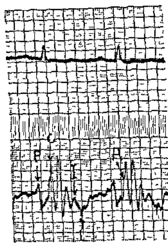


Fig 3-20(14). PACT with grade 3 abnormalities Seventy-four-year-old male Gastrectomy ECG old anteroseptal infarct, anterolateral ischemia. Accelerographic analysis early systole—tall C A and C are fused, early diastole—L is the deepest trough in the tracing, end diastole—tall P.

abnormalities Tracings abnormal in both systole and diastole reflect a higher degree of damage than those abnormal in systole only Tracings abnormal in early diastole probably indicate a high degree of disturbance.

Tracings with *respiratory variations* of amplitude and form should be considered more abnormal than those which do not display these variations The highest grade of pulsatory disturbance is represented by a grade 6 tracing plus respiratory variations and abnormalities in early diastole.

The *statistical incidence* of abnormal phases increases in the following order with progressive evidence of ischemia (1) midsystolic, (2) early-systolic, (3) end-diastolic, (4) end-systolic, (5) mid-diastolic, (6) early-diastolic

The statistical incidence of *midsystolic* ab-

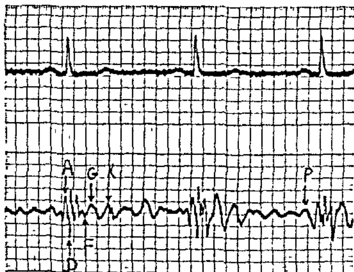


Fig 3-20(9). PACT with grade 2 abnormalities and respiratory variations Sixty-nine-year-old male with atypical episodes of precordial pain due to coronary heart disease. ECG- moderate ST-T changes Accelerographic analysis triple-peaked E. No 1 peak. Note respiratory variations (G, mid-diastole, and P)

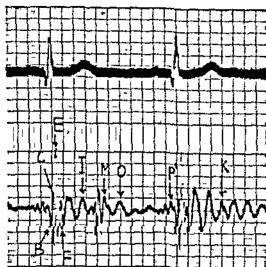


Fig 3-20(10). PACT with grade 3 abnormalities Eighty-five-year-old male with coronary heart disease ECG possible old high anterolateral infarct Accelerographic analysis. early systole—C is taller than G and I, midsystole—high-frequency oscillations between E and F, mid-diastole—tall, broad O Respiratory variations in early diastole (K-M) and end diastole (P).

8 Decrease of G below one-third of the amplitude of E [Fig 3-20(16)]

9. Rise of K above E [Fig 3-20(12)]

10 Descent of L below D and F [Fig 3-20(14)].

11. Rise of O above K [Fig. 3-20(10)]

12. Tall mid-diastolic deflections O and P [Fig 3-20(13)]

Variations in the amplitude of individual oscillations [G– Fig. 3-20(9); K– Fig 3-20(10), I– Fig. 3-20(7)].

Frequency criteria:

1 Partial increase in frequency; supernumerary oscillations [E– Fig 3-20(5), P– Fig 3-20(10)]

2 Partial decrease in frequency; lack of oscillations [I– Fig 3-20(6); K– Fig. 3-20(10)].

Time criteria:

1 Delay in the onset of accelerographic deflections over 0.01 sec The delay of peaks A, G, I, and K can be measured by direct comparison *with the electrocardiogram* [see Table 3-2(15)].

2 Early onset of peak K, short mechanical systole [Fig 3-20(7)].

Classification of Abnormal Tracings. Normal (grade 0) tracings are normal in each of the six phases of the cardiac cycle.

Borderline (grade 1) tracings may show any one of the above abnormal criteria in any one of the phases of the cardiac cycle The abnormality is limited to one phase of the cardiac cycle

Abnormal (grade 2 to grade 6) tracings are altered in more than one phase of the cardiac cycle The degree of abnormality is expressed by the *number of distorted phases. A* grade 2 tracing indicates the lowest grade of abnormality Grade 6 tracings are evidence of severe pulsatory disturbance

Distinction between two equally graded tracings is based on the presence of *diastolic*

of the connection between myocardial damage and graphic changes.

Low E peaks were observed in acute rheumatic carditis and in coronary heart disease [Fig 3-20(15)], and in dog experiments following toxic doses of isoproterenol and chloroform

The *I peak* disappears in the protracted hemorrhage of the dog and in many patients with hypertensive and coronary heart disease. The I peaks may reappear after bedrest and successful antihypertension treatment The absence of the I peak and T-wave abnormalities of the ECG may be independent from each other. It is possible that ventricular dilatation [illegible] 1937; Luisada). Peak I coincides in time with the peak of the precordial bulge described by Harrison in kinetocardiograms of coronary patients. A temporary (end-systolic) loss of contractility (no I wave) of the hypoxic area is the cause of the bulge, as the poorly contracting area is forcibly dilated by the contraction of the other ventricular sections.

The amplitude of the *mid-diastolic* waves of the PACT increases *with the rise of ventricular* diastolic pressure (animal *experiments*). The significance of large mid-diastolic oscillations [Fig 3-20(13)] is probably comparable to that of a triple *rhythm*. The relationship between the two phenomena, however, needs further studies.

Large *end-diastolic (presystolic) oscillations* (P) appear in a large percentage of hypertensive subjects and in the majority *of those with* coronary heart disease (Rosa). Mounsey found tall P waves in patients with mitral valve disease and left ventricular hypertrophy. It has been *mentioned* that Levophed electively increases the amplitude of these *end-diastolic* waves.

No P waves are present in atrial fibrillation. No *evidence* of a correlation between tall P peaks and a *presystolic* murmur was found Statistical data on the *occurrence* of a phonocardiographic 4th heart sound in hypertensive patients and those with coronary heart disease [illegible] of the accelerographic P wave.

The amplitude of the P peaks decreases with clinical improvement. Current data suggest that increased venous return, high end-diastolic pressure, and ventricular and atrial hypertrophy are instrumental in the origin of tall P waves.

Changes from the Usual Frequency Pattern. Supernumerary oscillations indicate an *increase in oscillatory frequency* during a given phase of the cardiac cycle The absence of one or more oscillations (*decrease in oscillatory frequency*) suggests either that no forces were originated or that certain forces have been cancelled out during a given period of the cardiac cycle [no I peak between G and K–Fig. 3-20(7)]. In animal experiments, isoproterenol increases the early-systolic (E-peak) oscillatory frequency. This has been attributed to left and right ventricular asynchronism and rise in right ventricular pressure. *Administration of Levophed* promptly restores the frequency *pattern* to normal. Premature ventricular contractions usually appear in bizarre frequency patterns [*Fig. 3-20(18)*]. *Splintered E* peaks are encountered in 40 *to* 80 per cent of coronary and hypertensive patients Splintered G peaks have been observed in cases of aortic stenosis.

Changes from the Usual Time Pattern. The *normal* upper limit of the time interval *between the Q of the ECG and peak E of the PACT* is 0.120 sec In 10 cases with complete left bundle branch block, an average of 0.138 sec was found.

The normal average duration of the A-C *segment of the* PACT is 0 029 sec In 26 cases with right bundle block an average of 0.036 sec was observed, and in 10 cases with left *bundle* branch block, an average of 0 055.

The prolongation of the A-K interval [Fig. 3-20(15)] or an early onset of K [Fig. 3-20(9)], as compared with the electrocardio*graphic Q-T* interval, occurs in coronary heart disease The pathophysiologic change underlying this graphic symptom may be similar to that of the *energetic* dynamic heart failure (Hegglin). In the author's *cases*, changes in the duration of the A-K segment were not necessarily connected with the prolongation of the Q-T interval.

Extreme *respiratory variations* seem to reflect abnormal hemodynamic responses to respiration in *either* the pulmonary or systemic circulation, or both

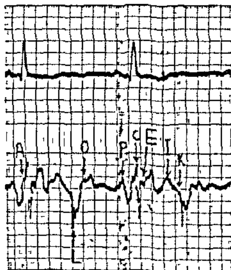


Fig. 3-20(15). PACT with grade 5 abnormalities. Seventy-four-year-old male with evidence of chronic coronary insufficiency and possibility of an old infarct. ECG. ST-T changes Accelerographic analysis early systole—tall C A and C are fused; midsystole—low E peak; early diastole—L is the deepest trough in the tracing, mid-diastole—tall O, end diastole—deep P-A segment

normalities is about 40 per cent in hypertensive patients and 61 to 87 per cent in those with coronary heart disease This is the most frequent type of abnormality. The early-diastolic phase is less frequently distorted than any other phase of the cardiac cycle.

PATHOPHYSIOLOGIC CORRELATES OF THE ABNORMAL PACT

Changes from the Usual Amplitude Pattern. The relationship between changes from the usual amplitude pattern of the accelerogram and abnormal intracardiac pressure levels is not fully understood. Changes in either right or left ventricular pressure generally result in amplitude changes of the PACT There is experimental evidence that the amplitude of precordial deflections closely follows intra-aortic pressure changes (Rosa and Kunos, 1956) during respiration Further studies are needed to clarify the role of intracardiac, intravascular, and intrathoracic pressures in causing changes of amplitude.

A gradual decrease in amplitude takes place with progressive *hemorrhage*. However, precordial waves abruptly *increase* at the terminal *shock level* of hemorrhage.

Levophed increases the amplitude of all oscillations, particularly those in end diastole.

Premature ventricular beats and *weak contractions* in mechanical alternans are accompanied by smaller waves. The same was noted after *large doses of chloroform.* Tall systolic and deep diastolic waves [Fig. 3-20(17)] were observed in *severe coronary insufficiency, acute rheumatic carditis, acute left heart failure,* and *acute pulmonary edema*

Studies of the author with experimental myocarditis or coronary embolization have revealed similar changes of the PACT, thus giving proof

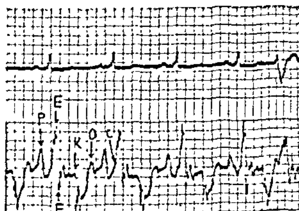


Fig. 3-20(16). PACT with grade 6 abnormalities Fifty-eight-year-old male. Acute pulmonary edema ECG old posterior infarction. Accelerographic analysis. early systole—A is absent, C is a notch superimposed on the ascending limb of E; midsystole—E consists of high-frequency vibrations; end systole—low, flat, or absent I peaks, early diastole—L is the deepest trough in the tracing; mid-diastole—prominent O; end diastole—tall P.

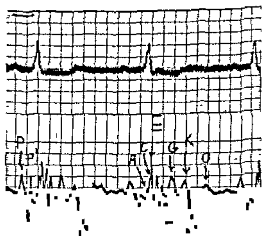


Fig. 3-20(17). PACT with grade 6 abnormalities Seventy-six-year-old male Acute pulmonary edema ECG old posterior infarction. Accelerographic analysis early systole—tall C C and E are fused, midsystole—high-frequency vibrations between E and F, end systole—no I peak, early diastole—deep L; mid-diastole—prominent O, end diastole—tall P.

of the connection between myocardial damage and graphic changes.

Low E peaks were observed in acute rheumatic carditis and in coronary heart disease [Fig 3-20(15)], and in dog experiments following toxic doses of isoproterenol and chloroform

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No P waves are present in atrial fibrillation No evidence of a correlation between tall P peaks and a presystolic murmur was found Statistical data on the occurrence of a phonocardiographic 4th heart sound in hypertensive patients and those with coronary heart d[illegible]

[illegible] to statistical findings on abnormalities of the accelerographic P wave

The amplitude of the P peaks decreases with clinical improvement. Current data suggest that increased venous return, high end-diastolic pressure, and ventricular and atrial hypertrophy are instrumental in the origin of tall P waves

Changes from the Usual Frequency Pattern. Supernumerary oscillations indicate an *increase in oscillatory frequency* during a given phase of the cardiac cycle. The absence of one or more oscillations (*decrease in oscillatory frequency*) suggests either that no forces were originated or that certain forces have been cancelled out during a given period of the cardiac cycle [no I peak between G and K–Fig. 3-20(7)]. In animal experiments, isoproterenol increases the early-systolic (E-peak) oscillatory frequency. This has been attributed to left and right ventricular asynchronism and rise in right ventricular pressure. Administration of Levophed promptly restores the frequency pattern to normal Premature ventricular contractions usually appear in bizarre frequency patterns [Fig 3-20(16)]. Splintered E peaks are encountered in 40 to 80 per cent of coronary and hypertensive patients Splintered G peaks have been observed in cases of aortic stenosis.

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Extreme *respiratory variations* seem to reflect abnormal hemodynamic responses to respiration in either the pulmonary or systemic circulation, or both

CLINICAL ASPECTS

Accelerography is a simple procedure. The accelerometer is an inexpensive instrument. All required supplementary equipment consists of a two-channel electrocardiograph The graphs are taken simultaneously with routine electrocardiography on any bed or table. No particular previous training of technicians is necessary. The procedure requires no more time than does a precordial lead in electrocardiography. The test does not impose inconveniences on the patient.

The benefits to be gained depend on training in reading tracings and on the coordination of graphic findings with all clinical and laboratory data. *Accelerography is a supplement to conventional diagnostic tools, not a substitute for them* Within these limitations, useful information on the pulsatory performance of the heart can be gained The reliability of accelerographic information depends on how clearly and accurately the clinical problem is considered

A first question is can a subject with a *normal* accelerogram be considered to have no cardiovascular disease? The answer is that only 2.4 per cent [Table 3-2(18)] of electrocardiographically documented patients with coronary heart disease have normal tracings and that none of those with (recent or old) myocardial infarction has normal tracings There is statistical evidence (Rosa et al., 1961) that *abnormal* precordial tracings do not occur in patients with no cardiovascular disease The probability of errors in coordinating tracings with clinical findings is extremely low

Borderline Tracings. Five per cent of subjects with no evidence of cardiovascular disease have borderline tracings. Causes underlying these minor distortions are unknown The distinction between near-physiologic and subclinical disturbance of the pulsatory mechanism requires further studies Borderline tracings in apparently healthy subjects may be an indication for further observation. Their significance in screening and prevention is self-evident. A series of patients with abdominal and pulmonary diseases has been found to have borderline tracings.

The interpretation of borderline tracings in patients with cardiac disease is empirical. Only one of the author's patients with recent myocardial infarction had a borderline precordial tracing. The recovery of this 39-year-old man was quick and uneventful A few patients with an old infarction or recent episodes of coronary failure had borderline tracings [Table 3-2(18)]. These patients showed less evidence of distress than those with an abnormal precordial tracing. It is, therefore, the author's impression that borderline tracings imply a more favorable prognosis

Abnormal tracings occurred in over 69 per cent of patients with hypertension and coronary heart disease with a normal electrocardiogram. It seems that arterial hypertension and ischemia frequently interfere with pulsatory ballistics However, this qualitative information in the presence of clinical symptoms would scarcely have more than theoretic value. In addition to this qualitative information, accelerography provides means to evaluate the *severity of the pulsatory disturbance*. There is some parallelism between the number of the graphic abnormalities and the severity of the clinical picture. Most (73.2 per cent) tracings taken from hypertensive patients are *normal, borderline, or grade 2*. These patients usually have few or no cardiac symptoms The majority (69 3 per cent) of patients with healed myocardial infarction have *grade 3 or grade 4 tracings*. Seventy-one and two-tenths per cent of graphs taken from patients with a recent infarction are *grade 4 to grade 6* Most patients with a grade 6 accelerogram have coronary disease with left heart failure or acute pulmonary edema

It should be emphasized that a considerable minority (roughly 30 per cent) of the tracings are either more or less distorted than the rest [Table 3-2(16)] Individual differences in pathophysiologic change may account for unusual accelerographic findings within apparently homogeneous groups. Table 3-2(19) shows blood pressure differences within a group of hypertensive patients Though the majority of tracings taken from hypertensive patients is grade 2 or less, blood pressure levels over 160/100 mm Hg may raise the percentage of abnormal phases to 58 per cent (three or more abnormal phases per tracing), even in patients with no clinical evidence of ischemia The incidence of abnormal tracings in patients with coronary heart disease is generally higher than in hypertensive subjects [Table 3-2(18)] It appears obvious that though graded classification allows some correlation of graphic symp-

TABLE 3-2(16). INCIDENCE OF CLASSIFIED PRECORDIAL TRACINGS IN NORMAL SUBJECTS AND IN PATIENTS WITH HYPERTENSION AND CORONARY HEART DISEASE

Condition	*Classification grade*	*Incidence, %*
Normal	0–1	100
Hypertension	0–2	73 2
Angina pectoris with normal ECG	2–3	57
Old infarct	3–4	69 3
Possible recent infarct	3–6	62 6
Definite recent infarct	4–6	71 2

TABLE 3-2(17) INCIDENCE OF DIASTOLIC ABNORMALITIES IN THE PACT IN NORMAL SUBJECTS AND IN PATIENTS WITH HYPERTENSION AND CORONARY HEART DISEASE

Condition	*No. of cases*	*Incidence of diastolic abnormalities, %*
Normal	79	0
Patients with noncardiovascular disease	17	5
Arterial hypertension, normal ECG	30	33 3
Arterial hypertension, abnormal ECG	90	53 3
Anginal syndrome, normal ECG	21	52 4
Anginal syndrome, abnormal ECG	82	80
Anginal syndrome + arterial hypertension, abnormal ECG	36	86 2
Anginal syndrome + chronic heart failure, abnormal ECG	25	76
Old myocardial infarction	56	94 7
Possible recent infarction	22	90 9
Definite recent infarction	39	100
Total	497	

toms with clinical data, an attempt should be made to correlate the "statistical" abnormality with the individual case This task can be achieved by (1) a study of the diastolic phases of the cardiac cycle, and (2) an analysis of the graphic variations due to respiration.

Table 3-2(19) reveals a practically linear correlation between the incidence of *diastolic abnormalities* on the one hand and arterial hypertension or myocardial ischemia on the other. Diastolic pulsatory disturbances are more frequent in patients with episodes of precordial pain than in hypertensive subjects. This holds true also for groups with a normal electrocardiogram.

The correlation between graphic symptoms and individual clinical case will be even more successful when *respiratory variations* are recognized as evidence of an inadequate hemodynamic response to respiration.

A few patients with severe coronary disease have no diastolic abnormalities [Table 3-2(17)], and many patients do not have abnormal respiratory variations Accelerography probably reveals some of the consequences of hypertensive and coronary heart disease Increased venous return, hypertrophy, dilatation, myocardial fibrosis, high diastolic pressure may or may not be present in individual cases, and probably the same holds true for accelerographic symptoms. Regardless of specific causes, some accelerographic patterns, just like increased venous return, may or may not be encountered in a number of conditions.

Accelerography is no diagnostic tool in terms of etiology, as graphic abnormalities of the *tracing reflect* abnormal function It has been shown that, statistically, the extent of the disturbance and abnormal timing may be characteristic of some clinical entities. It should be stressed, however, that no accelerographic differentiation of *hypertensive* patients from those with *coronary* heart disease is possible in the presence of left ventricular *strain*. Tracings of patients having *mitral stenosis* and myocardial fibrosis plus coronary insufficiency resemble those found in coronary heart *disease* On the other hand, some graphic abnormalities found in *valvular defects* seem to be characteristic Successful surgery in 230 patients with mitral stenosis (Rosa and Kunos, 1955b) and in 23 patients with patent ductus arteriosus (Rosa and Kunos, 1957a) resulted in a considerable postoperative decrease in the number of the previously observed accelerographic abnormalities

Many abnormalities (also in patients with coronary heart disease and hypertension) are reversible The reversibility of graphic data may be utilized for the evaluation of drug effects and of therapeutic measures. An in-

crease in the number of abnormalities compared to previous records indicated deterioration of functional efficiency. Tracings taken before, during, and after exercise tests—under study in this laboratory—show that exposure to work test in normal subjects *does not increase* the number of graphic abnormalities while cardiac patients respond with a deterioration of the tracing.

The foregoing data illustrate the necessity of correlating accelerographic data with all available information. That accelerography is a supplementary method does not detract from the value of information on the *extent* of functional impairment.

The clinical value of accelerography may be summarized as follows:

1. Statistical studies seem to demonstrate that borderline tracings reflect subclinical rather than near-physiologic conditions

2. Normal PACT tracings in documented coronary heart disease occur in only 2.4 per cent of the cases (or less)

3. No abnormal tracings are encountered in subjects with no evidence of heart disease

4. The incidence of moderately abnormal (grade 0 to grade 2) precordial tracings in hypertensive patients in early stages of the disease is extremely high (64 per cent).

5. Three out of four patients suffering from episodes of precordial pain and having a normal or borderline electrocardiogram have an abnormal precordial tracing. Patients with coronary heart disease have an abnormal PACT more often than hypertensive subjects With increasing hypertensive overload, the differences between the two groups decrease.

6. The number of graphic abnormalities—particularly those in diastole—shows a linear correlation with increasing clinical and electrocardiographic evidence of myocardial ischemia

7. Abnormal variations in shape (and amplitude) of the tracings do not occur in normal subjects.

8. Accelerography cannot be utilized in a differentiation between "ischemic" and rheumatic forms of heart disease.

9. It is the author's contention that the accelerogram reflects the extent of the cardiopulsatory-ballistic disturbance.

10. If exercise tests and follow-up studies reveal an increase in the number of graphic abnormalities, this should be accepted as evidence of temporary or progressive deteriora-

TABLE 3-2(18) OCCURRENCE OF CLASSIFIED PRECORDIAL ACCELERATION TRACINGS, AND PERCENTAGE OF OBSERVED GRAPHIC ABNORMALITIES IN NORMAL SUBJECTS AND IN PATIENTS WITH HYPERTENSION AND CORONARY HEART DISEASE

Group	*No of cases*	*Occurrence of classified tracings, %*			*Percentage of observed graphic abnormalities**
		Normal	*Borderline*	*Abnormal*	
Normal subjects ..	79	95	5	0	5.2
Patients with noncardiovascular diseases	17	0	100	0	17
Arterial hypertension:					
Normal ECG	30	4.1	32.5	63.4	26.1
Abnormal ECG	90	3.3	30	66.7	34.8
Anginal syndrome					
Normal ECG	21	23.8	9.5	66.6	34
Abnormal ECG	82	2.4	14.6	83	44.9
Anginal syndrome + arterial hypertension, abnormal ECG	36	2.7	19.4	77.9	50
Anginal syndrome + chronic heart failure, abnormal ECG .	25	0	0	100	53
Infarction:					
Old	56	0	3.5	96.5	54
Possible recent	22	0	4.5	95.5	62
Definite recent	39	0	2.5	97.5	68.3
Total	497				

* 100% = six abnormal phases per tracing

TABLE 3-2(19) CORRELATION BETWEEN PACT AND BLOOD PRESSURE LEVELS IN HYPERTENSIVE PATIENTS

Blood pressure, mm Hg		No of cases	Percentage of abnormal phases *
Systolic	Diastolic		
160+ or more	−100	99	35 5
−160	100+	75	40 0
160+ . . .	100+	47	58 0

* 100% = six abnormal phases

tion of the pulsatory function On the contrary, a decrease in the number of accelerographic abnormalities is evidence of improvement of the cardiac dynamics This can be used for evaluating the effect of surgical or drug therapy.

THE ACCELEROGRAPHIC REPORT

A scheme of reporting accelerographic findings is presented in Table 3-2(20). Some practical details on the use of this scheme will be discussed here.

TABLE 3-2(20). THE ACCELEROGRAPHIC REPORT

Respiratory variations	*yes*	*no*
Diastolic abnormalities	*yes*	*no*

Analysis of abnormalities

Cardiac phase	Abnormal		
	Amplitude	Frequency	Time pattern
Early systole: A–C			
Midsystole: C–G ..			
End systole: G–K .			
Early diastole: K–O .			
Mid-diastole O–P			
End diastole, P–A .			

Classification grade. [0] [1] [2] [3] [4] [5] [6]

Remarks

Respiratory Variations. The accelerogram is a dynamic rather than a static reflection of pulsatory-ballistic forces. It is, therefore, helpful to observe 10 to 12 consecutive heart beats instead of a single one for analysis. When doing so, the examiner will discover a gradual increase in the amplitude of subsequent contractions during inspiration. Expiration, on the contrary, will result in a gradual decrease. The variations in amplitude—and sometimes in shape—are smooth and gradual in normal subjects. Respiration does not change the dominant graphic pattern, all contractions being comparable to the others.

Each of the six phases of the cardiac cycle should be compared with identical phases of subsequent contractions. Minor variations, as well as major abnormal changes, have a recurrent pattern, appearing again and again with the return of the respiratory phase.

Peak A may be hidden or fused with peak C for several contractions. It will reappear whenever expiration separates the two peaks from each other. The same may be true for M and N, usually small in normal subjects.

With adequate instrument and standardized technique, the accelerogram contains few, if any artefacts. Even small and seemingly insignificant notches recur regularly in long strips, thus facilitating a distinction from technical artefacts.

Analysis of the Frequency Pattern. Each directional change of the tracing, as well as sudden transitions from heavy to fine lines [peak K in Fig 3-20(5)] or small notches [C in Fig 3-20(3)], should be labeled in chronologic order. The theoretic accelerogram of a *young, healthy* subject should consist of smooth, fine lines ending in pointed or rounded peaks and troughs. A fair approximation of this ideal pattern can be observed in young, healthy children This simplifies the identification of individual deflections and facilitates the recognition of abnormalities in the frequency pattern.

Split A, C, and M are abnormal No tripled peaked oscillations have ever been observed in any phase of the cardiac cycle of normal subjects *The amplitude* criteria of normal and abnormal tracings have been described in detail (see previous text).

A correlation of the normal time relationships

of PACT waves with those of the electrocardiogram [see text and Table 3-2(15)] is helpful in recognizing an abnormal tracing Special attention should be paid to the timing of peaks C, G, I, and K.

Description of Individual Phases. Each of the six phases of the cardiac cycle can be described by putting a check mark for each abnormality in the respective column of the report. Table 3-2(20) contains three columns for each phase of the cardiac cycle. The purpose of the scheme is to provide comprehensive information on all observed abnormalities. In Fig. 3-20(7), for example, the lack of peak I has been interpreted as an abnormal end-systolic *frequency pattern* (decrease in oscillatory frequency) In addition, peak K arrives earlier than the end of the electrocardiographic T wave. This is an abnormal end-systolic *time pattern* The two types of abnormality should be marked by separate check marks, one in the column of the frequency pattern and one in that of the time pattern

The graded classification of a tracing is based on the number of abnormal phases, regardless of the number of the abnormalities [see Table 3-2(20)]. Seven grades of classification (from grade 0 to grade 6) qualify the tracings. Moreover, diastolic abnormalities and large respiratory variations add further means of qualification.

As a classification based on 18 grades would be confusing, the author has suggested that only grades 0 to 6 be used for classification, the check marks can be utilized as a visual facility in comparative or follow-up studies On the other hand, the number of abnormal patterns, like the number of abnormal phases, may help in a finer appraisal of the extent of the pulsatory disturbance.

In some cases, borderline or questionable criteria of abnormality may be present. Peak I in Fig. 3-20(7) (first contraction) is absent The early onset of peak K, a second abnormal pattern, confirms that the end-systolic phase is indeed abnormal.

The column of the report observed for "remarks" may specify some abnormalities of special interest or importance Arbitrary and subjective interpretations should be avoided, diagnostic and prognostic announcements, as well as administration of preventive and therapeutic measures, come under the province of the physician in charge of the patient.

8

Percussion and roentgenology

Percussion

CESARE FRUGONI AND VITTORIO PUDDU

Fluoroscopy

PEDRO COSSIO

Roentgenography and Orthodiagraphy

JOHN B. SCHWEDEL

PERCUSSION

HISTORY

"Thorax sani hominis sonat, si percutitur. . . At ubi cor situm pro parte obtinet, quandam plenitudinem sonus exhibet manifeste indicans: solidiorem cordis partem ibi locatam vividam resonantiam pro parte obtundere. . Quando cor ita distenditur, a sanguine in ventriculis et auriculis cumulato, ut illos propellendo impar evadat, tunc saepe expanditur in incredibilem molem distensionem hanc, Aneurisma Cordis appellare placuit . . Signum patognomonicum hujus mali est, quod locus (ubi cor situm obtinet) percussus in magna circumferentia carnis percussae sonitum exacte referat."[1] These sentences represent the first description of *cardiac percussion* and are reproduced from the Monograph of Auenbrugger (1704–1776) published in Vienna in 1761

This method was almost completely unknown for many years Its diffusion was due to the authoritative voice of Corvisart, Napoleon's physician, who published a French translation of Auenbrugger's pamphlet (1808) and increased its value with excellent comments A refinement of percussion technique was made by Piorry (1794–1879) with the invention of the *pleximeter,* a small device which nowadays is practically forgotten. Piorry also is credited with describing the palpatory impression which one receives during percussion

The classical history of percussion is practically completed by the acute physical and semeiological study contained in Skoda's textbook of percussion and auscultation

PHYSICAL PRINCIPLES AND TECHNIQUES

Whenever the chest is percussed over resonant areas, an ellipsoid area of pulmonary tissue starts vibrating This area has a longitudinal axis perpendicular to the surface under percussion (Fig. 3-21). It has a depth which is proportional to the intensity of percussion but is not greater than about 4 cm, it has a base which is smaller or larger depending on whether an intercostal space or a rib was percussed, and also on the intensity of percussion The characteristics of the sound which is elicited vary according to *the air content of the lung* and *the force of percussion* If the density of the lung and the intensity of percussion are constant, this sound becomes more high-pitched, weaker, and shorter whenever the area includes cardiac tissue, i e , a tissue which has no air and cannot vibrate The change of

[1] "The thorax of a healthy man sounds if it is percussed . . Where the heart is located, complete dullness is elicited, indicating an arrest in the vibrations . . When the heart dilates because of [illegible] ... [illegible] of this pathological process can be found in an enlargement of the cardiac dullness"

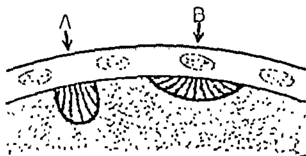


Fig. 3-21. The vibrant area created by percussion is narrower if the latter hits an intercostal space, A, than if it hits a rib, B.

sound in such cases depends upon the decreased area of vibrating pulmonary tissue This is the principle of *topographic percussion* which enables one to recognize the borders of the heart and those of the lungs overlapping the heart itself.

There is another type of percussion, called *comparative percussion* which enables one to recognize variations of density in tissues which are only partly aerated, as in various areas of the lung. This is impossible when dealing with the heart, an organ which does not contain air, is incapable of vibrations, and can only give rise to completely dull sounds, i e, no sounds

From the above-mentioned physical principles arise the essential points of the technique of percussion and the criteria of clinical evaluation of the method. If the cardiac borders are *distant from the chest wall*, in order to recognize them, one should use a *relatively strong percussion*, so that the explored area becomes deeper. However, percussion should not be so strong as to cause vibration of masses of air which are external to the lungs, especially the air bubble contained in the stomach, also, it should not broaden excessively the base of the ellipsoid which is put into vibration If, however, the borders which one is trying to recognize are *near the wall*, it is better to use a *weak percussion*, which, as is known, narrows the base of the vibrating ellipsoid and increases the accuracy of its delineation

It is impossible to delineate by means of percussion any cardiac borders at a depth greater than 4 cm from the internal surface of the chest wall. Therefore, the image of the cardiac borders which is drawn on the chest wall does not correspond to the roentgenographic projection of the cardiac silhouette. It should correspond to the projection of that section of the heart which is at a depth of 4 cm from the chest wall (Fig. 3-22).

In order to avoid broadening the base of the vibrating area, with a resulting loss of precision, it is preferable to percuss the intercostal spaces instead of the ribs, and to use moderate force of percussion In order to recognize the pulmonary margins above the heart, it is necessary to use *extremely weak percussion*, so as to cause vibration in as small an amount of lung tissue as possible.

The area corresponding to the projection onto the precordium of the deep borders of the heart (obtained by deep percussion) is called the *area of relative dullness* It corresponds to the minimal reduction of percussion sound in comparison to the sonority obtained over the pulmonary tissue at a distance from the heart The area corresponding to the projection onto the precordium of the cardiac area bordered by the pulmonary margins (obtained by superficial percussion) is called the *area of absolute dullness* Within this area, the sound is absolutely dull because only tissues which are completely without air (chest wall and heart), are percussed.

Percussion is usually performed with the patient in a supine position; a sitting position is less practical. It may be useful to study the cardiac borders (relative dullness) with the patient on his right or left side in order to

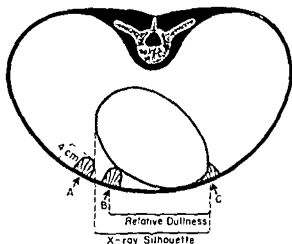


Fig. 3-22. A The area of dullness corresponding to the right border of the heart is usually smaller than the same area obtained through fluoroscopy. This is because the area which vibrates through percussion does not reach the deepest parts of the heart but only those nearer to the chest wall, B. On the left, on the contrary, the limits obtained by percussion and radiology may be similar, C.

observe displacement of the heart. It may also be useful to perform the percussion of the pulmonary borders (absolute dullness) in deep inspiration and expiration in order to observe the expansion of these margins

Both Auenbrugger and Corvisart percussed the chest directly with four fingers of the hand bent and united. Piorry, with his pleximeter, introduced the method of *mediated percussion* Nowadays, percussion is usually performed with only one finger of the right hand this is bent and hits the end of the terminal phalanx of a finger of the left hand, this is extended and applied with medium or strong pressure on the chest The finger which acts as a pleximeter should be parallel to the margin which *is to be determined* During percussion, one should appreciate, in addition to the variation of sound, also *the variation of palpatory impression* In order to reduce the area put into vibration, one can also place the finger, which is acting as a pleximeter and is completely bent at the first joint and extended at the second, in a position which is perpendicular to the surface of the chest wall (*pointed percussion*, Fig 3-23)

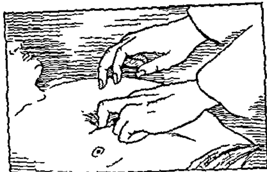


Fig. 3-23. "Pointed" percussion. (From Martini)

Recognition of the *left cardiac border* is usually preceded by palpatory search for the apex beat If this is not felt in a supine position, the patient should be placed for a few moments on his left side When the apex beat is located, one should percuss along a series of lines placed as the spokes of a wheel and converging toward the apex beat One should start percussion at least 10 cm from the point which is under study and proceed from the left side toward the midline, from the highest points toward the lowest, and from the lowest points toward the highest Percussion should be rather light. Proceeding along each spoke and ending at the first reduction of sound, one will obtain a *line* which corresponds roughly to the area of the apex and to the lower and left margins of the heart The detection of part of the lower margin near the apex is frequently possible because cardiac dullness is contrasted with the tympanic sound of the air bubble contained in the gastric fundus here percussion should be extremely weak because of the high sonority of this gas bubble Sometimes it is impossible to percuss the lower margin because its dullness is confused with that of the left lobe of the liver.

The rest of the left margin of the heart is located by repeating the percussion along lines which *run perpendicular to the margin* which is to be delimited, always *proceeding from the lateral and higher areas toward the heart*.

The percussion of the *right margin* should be preceded by the percussion of the upper margin of hepatic dullness which is obtained by percussing from above downwards over the right chest, and with strong percussion This margin does not correspond to the position of the diaphragmatic dome which is higher and cannot be reached by percussion because of its distance from the chest wall After finding this margin, which is roughly horizontal, one should percuss above it along a series of lines from the right side of the chest toward the sternum A right margin which is grossly vertical is usually obtained This margin forms with the hepatic margin a right angle which is called the *cardiohepatic angle*.

Thus, it is possible to draw over the chest a roughly triangular scheme which is complete in its left and right limits and is open downwards and upwards This scheme can be closed below by connecting the cardiohepatic angle with the lowest and innermost point of the area of the apex by means of a straight line. On top, this area can be completed percussing from above downwards over the manubrium of the sternum until cardiac dullness is reached (Fig 3-24).

NORMAL LIMITS OF RELATIVE CARDIAC DULLNESS ANATOMICAL CORRELATIONS

Left Border. The apex is usually from 8 to 11 cm from the midsternal line, in the 4th or 5th intercostal space, at or within the left midclavicular *line*. Above the apex, the left border runs upwards and inwards with a slightly convex profile until it meets with the

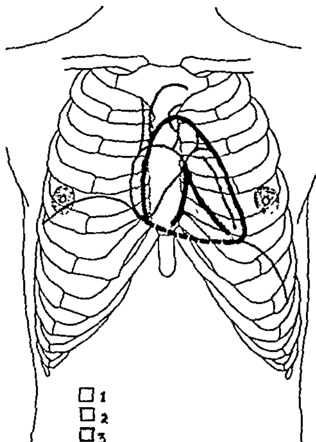


Fig. 3-24. Schematic relationship between anatomical projection of the heart and vessels on the anterior chest wall and the absolute and relative areas of dullness: 1, Part of the heart which cannot be recognized through percussion, being too deep. 2, Area of relative dullness. 3, Area of absolute dullness.

upper border. In the 3d left *interspace* this margin is usually not more than 3 5 to 4 5 cm from the midsternal line The left border *of the heart is normally formed in its lowest* part *by the margin* of the left ventricle, above this, by the outflow tract of the right ventricle and *the trunk of the* pulmonary artery.

Right Margin. This is normally situated *not* more than 1 cm outside the right margin of the *sternum It corresponds to the right atrium.*

Upper Margin. This is usually at the level of the 3d rib and corresponds to the point of origin of the large vessels

COMPARISON OF CARDIAC BORDERS DETERMINED BY PERCUSSION AND ORTHODIAGRAPHY IN NORMAL SUBJECTS (FIG. 3-24)

In the normal individual with a chest wall of normal thickness, there is fairly good correspondence between the borders of the medial and high part of the left margin obtained by percussion and those revealed by orthodiagraphy. The apex is usually placed by percussion from 0.5 to 1 cm outwards from its actual position. The right border obtained by percussion does not correspond to the orthodiagraphic border because it is too far from the chest wall to be reached by percussion. Under *normal conditions, there is a difference of about* 2 cm between the right border obtained by percussion and that obtained by orthodiagraphy.

VARIATIONS IN RELATIVE DULLNESS

Extracardiac Causes. An unusual thickness of the chest wall due to fat or large size of the left breast may impair the transmission of the *percussion sound and render percussion* rather uncertain. Deformities of the sternum and of the anterior chest wall in general may variously modify the normal dimensions of relative cardiac dullness A high degree of pulmonary emphysema may render cardiac percussion impossible by *interposing* a thick *layer of* pulmonary tissue between chest wall and heart and by *increasing* the sonority of the lung In the same way, the existence of fluid in the pleural cavities may make percussion impossible because dullness of the fluid and cardiac dullness may be adjacent. Severe *bloating of* the stomach or colon, or the existence of a pneumothorax, may also yield false data Finally, a pneumothorax or the retraction of a lung border may modify the borders of the *heart* by displacing this organ.

Physiologic Cardiac Causes. These are physiologic modifications of shape and position of the heart which reach their extremes in the "vertical heart" and "horizontal heart."

Pathologic Cardiac Causes. These variations usually cause an increase in the area of cardiac *dullness. They may be due to pericardial* effusion, diffuse cardiac *enlargement,* or sectional enlargement of the heart

Pericardial effusion usually causes a global enlargement of the area of relative dullness If the effusion is very abundant, the cardiohepatic angle becomes obtuse. A displacement towards the left of the left margin may be due to enlargement of either *the left ventricle* or *the right.* In the first case, the cardiac apex is much lower than in the second, in which the apex is usually displaced towards the left.

The outward displacement of the upper left margin in the 3d left interspace, especially if accompanied by slight or no enlargement of the lower part of the same margin, indicates *an enlargement of the outflow tract of the right ventricle and of the trunk of the pulmonary artery.* It has been described in cases of mitral stenosis (*sign of Grocco*) and of patent ductus arteriosus A displacement of the right border toward the right is due to *enlargement of the right ventricle, the right atrium, or both* It is found in mitral stenosis, tricuspid valve diseases, interatrial septal defect, many cyanotic congenital diseases, and chronic cor pulmonale.

An increased area of cardiac dullness in all directions, when it is not due to pericardial effusion, indicates a *diffuse cardiac enlargement.*

Changes of Position of the Heart. In lateral decubitus, the borders of cardiac dullness are normally displaced by about 2 cm toward the side which is lower when the patient is supine. This mobility of the heart *may be absent* in patients with adhesive pericarditis where connections between pericardium, pleurae, and mediastinum have developed (*accretio*). However, it may still be present if the adhesions are loose and in cases where adhesions have formed between the heart and the pericardium (*concretio*). If the heart is very large because of *severe dilatation* of its chambers, the above-described mobility may be absent even though there are no pericardial adhesions. When the patient moves from the supine to the sitting position, there usually is a slight increase of relative dullness. If there is pericardial effusion, the contour of the area of dullness may be greatly modified and take the shape of a hot water bag

ABSOLUTE CARDIAC DULLNESS AND ITS VARIATIONS

In normal subjects, the area of absolute dullness which corresponds to that surface of the heart which is not covered by the pulmonary margins has a triangular shape with a corner directed upward and a left border at about 5 cm from the midline, the right border is approximately at the left sternal margin, another corner is at the lowest margin of the 4th rib. The lower border corresponds to that of relative dullness, i e , the theoretical line drawn from the cardiohepatic angle to the apex. The determination of the area of absolute dullness has little value in regard to cardiac disease because its variations are mostly due to modifications of the lungs or pleurae This dullness disappears often in pulmonary emphysema, and frequently in cases with pneumothorax In cases of constrictive pericarditis with adhesions to the sternum, there may be no variations of the margins which occur normally in deep respiration. However, the same design may occur whenever there are pleural adhesions or sclerotic changes of the lungs.

PERCUSSION OF THE LARGE VESSELS ABOVE THE HEART

Under normal conditions, there is a clear pulmonary sound of percussion over the sternal manubrium and on each side above the 3d rib The existence of dullness in these areas may be due to enlargement or displacement of the aortic arch It is common in aortitis and aortic aneurysms Obviously, dullness of the same area may be caused by other diseases (retrosternal goiter, mediastinal tumors, etc.).

DORSAL PERCUSSION

This type of percussion was anticipated by Piorry as an integration of frontal and lateral percussion for an exact determination of the cardiac volume. Dorsal percussion was studied by some authors but is now nearly abandoned It was performed in the left paravertebral region at the level of the 6th and 7th dorsal ribs, and was supposed to reveal enlargement of the left atrium. It may be of interest in severe mitral stenosis It may also reveal enlargement of the descending aorta due to diffuse aortitis or aneurysm

PRACTICAL CONSIDERATIONS

The part played by percussion in examination of the heart has completely changed in the last 75 years. Percussion was described in 28 pages of the textbook by Eichhorst (1892); 7 pages in the cardiology textbook by Vaquez (1928); and one-third of a page in Friedberg's book (1956). The reasons for this decrease are multiple. (1) the ever-increasing use of x-ray methods so that fluoroscopy of the chest is now part of the current physical examination; (2) the numerous causes of error which decrease the accuracy of percussion, (3) the fancy refinements of percussion indulged in by

great cardiologists of the past, who tried to obtain from percussion techniques data that could not be supplied using such methods.

Is it advisable to abandon completely percussion, to forget what has been learned from past teachers, to abolish it in modern medical classes? The authors believe that this would be a mistake for the following reasons: (1) Each type of knowledge, even though containing only part of the truth, represents an heirloom of human ingenuity which should not be destroyed. (2) Classic semeiology, even though left behind by modern technical methods, is still a good tool of education which helps in the training of students who should learn to observe and to perfect their senses. (3) Percussion enables the cardiologist to obtain a rapid, even though approximate, orientation in regard to the size and shape of the heart; this is particularly important whenever he cannot make use of a fluoroscope. For example, in the home examination of a patient who has had a recent myocardial infarction, immediate determination of the size of the heart may have importance for prognosis and therapy.

It is self-evident that one should always keep in mind the multiple causes of error and the differences between the results obtained by percussion and orthodiagraphy. In particular, one should not try to evaluate by means of percussion small changes in size and shape of the heart or to solve delicate diagnostic problems, like the evaluation of a systolic murmur. In all doubtful cases, and whenever possible, one should obtain a roentgenographic examination. However, one should not forget that, in special cases, as in pericarditis with effusion, percussion may supply data which may be even superior to those supplied by x-ray studies.

FLUOROSCOPY

Radiological exploration is one of the indispensable and fundamental methods of cardiovascular examination. The situation of the heart and great vessels between the lungs, which are transparent to roentgen rays, permits the evaluation of its contours under different angles and, thanks to this, the study of the location, form, size, and pulsations of the various parts of the cardiac silhouette.

METHODS AND TECHNIQUE

For *routine examination*, no preparation or complicated apparatus is necessary. As a complement, one can use the ingestion of a thick radiopaque substance (barium swallow) in order to visualize the esophagus and thus evaluate the position of the left atrium and the descending aorta, which are near this organ.

Radiological examination should begin with *fluoroscopy* (see also Chap. 8, Roentgenography and Orthodiagraphy) whenever possible, with the subject standing first in a *posteroanterior* (*PA*) *position* (also called frontal position). Then, the patient should be turned toward the left under observation, until the appearance of the clear retrocardiac space; this position is called *right anterior oblique* (*RAO*). Finally the patient should be turned toward the right until the clear retrocardiac space is seen, this position is called *left anterior oblique* (*LAO*) (Fig. 3-25). If necessary, the rotation of the patient can go beyond these angles and the patient may be placed in a completely *lateral position*.

In each one of these three main positions, an x-ray picture should be taken at a minimum distance of 1.80 m (6 ft) between the x-ray plate and the tube in order to avoid distortion of the cardiovascular silhouette due to the divergence of the rays from their point of origin (*teleoroentgenogram*). Similar results are obtained by using a sliding central ray, i.e., by tracing an *orthodiagram* (See Chap. 8, Roentgenography and Orthodiagraphy.)

NORMAL CARDIOVASCULAR SHADOW

The heart and large vessels are projected as a dense uniform shadow with clean-cut pulsating contours standing out in the clear field of the lungs, continuing upwards with the shadow of the organs of the neck, and downwards with that of the abdominal organs. Its aspect changes fundamentally with the positions in which it is examined.

Frontal Position. The cardiovascular shadow, located between the lungs, is superimposed on the shadows of the vertebral column and sternum, but within it one may individualize the clear spaces of the trachea and the two main bronchi (Fig. 3-26B).

Elongated in its upper position and ovoid in its lower, it lies almost horizontally over the

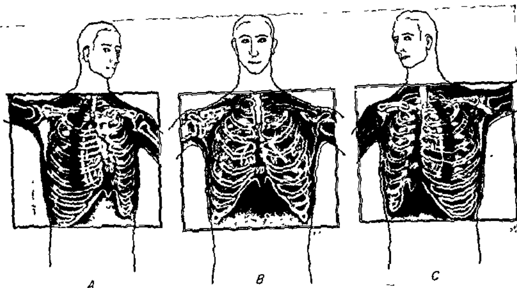


Fig 3-25 Positions for fluoroscopy. A. Right anterior oblique (RAO). B Posteroanterior (PA). C. Left anterior oblique (LAO).

diaphragm in stocky individuals (*horizontal heart*), and almost vertically in slender persons (*vertical heart*). In the latter instance, at times the heart does not reach the diaphragm and appears to be hanging (*drop heart*). At about middle level, two shadows are projected like butterfly wings, the so-called *hilar shadows* (or pulmonary hili), chiefly constituted of the stems of the pulmonary arteries.

In the main cardiovascular shadow, two borders can be recognized, the right and the left.

The *right border* consists of two arcs of about the same dimension but of different curvature. The *lower arc*, more pronounced, swings from the diaphragm to the right hilus, corresponding to the projection of the *right atrium*. Only in slender individuals is the lower end straight, being due to the projection of the shadow of the *inferior vena cava*. The *upper arc*, much less pronounced and at times almost straight, extends from the right hilus to the clavicle and is due to the projection of the *superior vena cava*, except in the lowest part, which may be due to the projection of the *ascending aorta*, in which instance it is slightly more curved.

The *left border* is composed of three arcs, lower, middle, and upper, of different dimensions and curvatures. The *lower arc* has an external convexity corresponding to the *left ventricle*, extending from the left diaphragm to a point called *the point of opposite pulsations*, where the systolic retraction of the ventricle ends and the systolic expansion of the large arteries begins. Sometimes the cardiophrenic angle is filled by a shadow

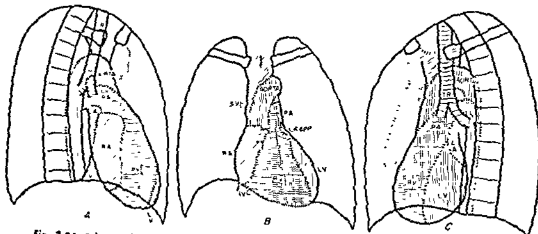


Fig. 3-26. Scheme of the cardiovascular structures revealed by fluoroscopy. A. = RAO. B. = PA. C. = LAO. (From Parkinson, Brit. M. J., 1933.)

great cardiologists of the past, who tried to obtain from percussion techniques data that could not be supplied using such methods.

Is it advisable to abandon completely percussion, to forget what has been learned from past teachers, to abolish it in modern medical classes? The authors believe that this would be a mistake for the following reasons. (1) Each type of knowledge, even though containing only part of the truth, represents an heirloom of human ingenuity which should not be destroyed. (2) Classic semeiology, even though left behind by modern technical methods, is still a good tool of education which helps in the training of students who should learn to observe and to perfect their senses. (3) Percussion enables the cardiologist to obtain a rapid, even though approximate, orientation in regard to the size and shape of the heart, this is particularly important whenever he cannot make use of a fluoroscope. For example, in the home examination of a patient who has had a recent myocardial infarction, immediate determination of the size of the heart may have importance for prognosis and therapy.

It is self-evident that one should always keep in mind the multiple causes of error and the differences between the results obtained by percussion and orthodiagraphy. In particular, one should not try to evaluate by means of percussion small changes in size and shape of the heart or to solve delicate diagnostic problems, like the evaluation of a systolic murmur In all doubtful cases, and whenever possible, one should obtain a roentgenographic examination. However, one should not forget that, in special cases, as in pericarditis with effusion, percussion may supply data which may be even superior to those supplied by x-ray studies.

FLUOROSCOPY

Radiological exploration is one of the indispensable and fundamental methods of cardiovascular examination The situation of the heart and great vessels between the lungs, which are transparent to roentgen rays, permits the evaluation of its contours under different angles and, thanks to this, the study of the location, form, size, and pulsations of the various parts of the cardiac silhouette

METHODS AND TECHNIQUE

For *routine examination*, no preparation or complicated apparatus is necessary. As a complement, one can use the ingestion of a thick radiopaque substance (barium swallow) in order to visualize the esophagus and thus evaluate the position of the left atrium and the descending aorta, which are near this organ.

Radiological examination should begin with *fluoroscopy* (see also Chap 8, Roentgenography and Orthodiagraphy) whenever possible, with the subject standing first in a *posteroanterior (PA) position* (also called frontal position) Then, the patient should be turned toward the left under observation, until the appearance of the clear retrocardiac space, this position is called *right anterior oblique (RAO)* Finally the patient should be turned toward the right until the clear retrocardiac space is seen, this position is called *left anterior oblique (LAO)* (Fig. 3-25). If necessary, the rotation of the patient can go beyond these angles and the patient may be placed in a completely *lateral position.*

In each one of these three main positions, an x-ray picture should be taken at a minimum distance of 1 80 m (6 ft) between the x-ray plate and the tube in order to avoid distortion of the cardiovascular silhouette due to the divergence of the rays from their point of origin (*teleoroentgenogram*) Similar results are obtained by using a *sliding central ray, i e, by tracing an orthodiagram* (See Chap 8, Roentgenography and Orthodiagraphy)

NORMAL CARDIOVASCULAR SHADOW

The heart and large vessels are projected as a dense uniform shadow with clean-cut pulsating contours standing out in the clear field of the lungs, continuing upwards with the shadow of the organs of the neck, and downwards with that of the abdominal organs Its aspect changes fundamentally with the positions in which it is examined

Frontal Position. The cardiovascular shadow, located between the lungs, is superimposed on the shadows of the vertebral column and sternum, but within it one may individualize the clear spaces of the trachea and the two main bronchi (Fig 3-26B).

Elongated in its upper position and ovoid in its lower, it lies almost horizontally over the

tures, there is a clear area called the *retrocardiac space*, in which, at times, it is possible to recognize the band of the descending aorta (Fig 3-26A) Two borders are clearly visible the *anterior*, which stands out in the pulmonary field, and the posterior, in front of the vertebral column.

The *anterior border* is formed by three arcs The lower is rather straight and almost vertical, representing the left or right ventricle according to the degree of rotation and the body build of the subject. The middle arc is more curved but more inclined backwards, and corresponds to the *pulmonary artery* The superior arc is almost straight and somewhat more vertical, representing the ascending aorta and continuing backwards with the descending aorta (when the latter is visible), although generally it is interrupted by the clear space of the trachea

The *posterior border* is represented by a *single* arc: below and near the diaphragm, it is formed by the inferior vena cava or right atrium, according to the body build of the subject, the upper portion corresponds to the *left atrium*

The ingestion of a radiopaque substance shows the esophagus traversing the *retrocardiac* space almost vertically and with a slight forward curvature, particularly in its lower third Its borders are *parallel*, except that in front of the aorta, one can see the aortic notch and, immediately below, there is another similar notch corresponding to the segment of the esophagus which is in intimate contact with the *right bronchus*.

Left Anterior Oblique Position (LAO). The left anterior oblique position shows the cardiovascular shadow as elongated as it is in RAO, but to the *left* of the vertebral column Here also a clear retrocardiac space is seen, but this is narrow and sometimes only appreciable in deep inspiration (Fig 3-26C) Two borders are visible, anterior and posterior.

In the *anterior border*, there are two arcs The lower, more curved and longer, is constituted entirely by the right atrium, except in its upper portion where sometimes the right auricular appendage may be projected *The upper* arc, almost vertical and less curved, is due to the ascending aorta which curves backwards toward the shadow of the vertebral column, but is interrupted by the clear space of the *trachea*; *this* continues with the main bronchi, the right directed forwards, and [illegible]

sponds to the interventricular sulcus, *just* at the level of the diaphragm in deep inspiration; the upper corresponds *to* the atrioventricular sulcus. The lower arc is produced by the right ventricle, the *middle* by the left ventricle, and the upper by the *left atrium The clear space enclosed between the ascending* aorta, the aortic arch, and the descending aorta (or perhaps the vertebral column) is called the *aortic window*. The ingestion of a radiopaque substance shows the esophagus in the retrocardiac clear space with characteristics similar to those in RAO, except that the aortic notch, *for obvious reasons*, may appear on the *posterior border*

MODIFICATIONS OF THE CARDIOVASCULAR SHADOW

The cardiovascular shadow may present *modifications in situation, form*, size, density, pulsations, and mobility of the heart and large vessels, as well as in the vascular structure of the lungs.

Situation. The cardiovascular shadow may be displaced upward, *to the left, or to the* right, either without inversion of its *chambers (acquired dextrocardia)* or with inversion, in such a case, the apex is often formed by the arterial ventricle (*congenital dextrocardia*).

The elevation of the heart places this organ in a more horizontal position, it is generally due to rise of the left hemidiaphragm because of phrenic paralysis or increase in intraabdominal *pressure* (meteorism, ascites, pregnancy, or large tumor); only exceptionally is it caused by fibrous retraction of the upper lobes of both lungs

Displacement of the heart to the left (*levocardia*) generally produces a more vertical position and is produced by thoracic deformities such as dorsal scoliosis with convexity toward the right or funnel chest, as well as by *retraction* of the left chest (*atelectasis*, *fibrosis*) or expansion of the right (pleural effusion, pneumothorax) *Dextrocardia* may also be due to deformity of the chest wall, such as dorsal scoliosis with a *left* convexity or to the above lesions, acting *of course in the opposite direction* Congenital dextrocardia can occur along with inversion of all the *other* viscera (*situs inversus*) or with only involvement of the heart and its vessels (*isolated dextrocardia*) or of the heart alone, the aortic arch remaining on the left (*mirror heart*) The reverse may also occur, in which the heart is on *the left* and the aortic knob on the right (*right aortic arch*). While

called the *perapical triangular shadow*, caused by pericardial fat or pericardiodiaphragmatic connections. One should know how to identify this structure in order not to confuse it with the shadow of the left ventricle itself. The *middle arc* continues upward above the lower. It is due to the projection of the *pulmonary trunk*, except in its lowest end, where a small segment may correspond to the projection of the *left auricular appendage*. It ends where the upper arc begins, this is called the *aortic bulge* and is due to the projection of the aortic arch in its backward course.

Each arc of each border presents pulsations of different amplitude and direction. The pulsations are greater over the left border, but the direction is not the same in the different arcs While the lower (or left ventricular) arc rapidly retracts during systole and more slowly expands during diastole, the middle and the upper arcs pulsate in the opposite direction. This is well displayed at the point of opposite pulsations.

Over the right border, the pulsations are smaller and less precise, those of the lower arc correspond to the contraction of the right atrium plus traction by the right ventricle, and those of the upper to the pulsations of the superior vena cava The lower part of the upper arc, particularly in horizontal hearts, may show the systolic pulsations of the ascending aorta

The cardiovascular shadow may present two other types of movement, not related to its own pulsations. Some of these are intimately related to respiration and others to changes in position. During *inspiration*, and more so if it is forced, the whole cardiac shadow becomes narrower due to the approach of its contours toward the midline while the apex becomes separated from the diaphragm. During deep expiration, the opposite movement occurs. In *dorsal decubitus*, the borders are more widely separated and more curved while the apex is buried within the shadow of the diaphragm In *left lateral decubitis*, the heart is displaced about 2 cm to the left, particularly in regard to the left ventricular arc. In *right lateral decubitus*, the same displacement occurs toward the right, with the main displacement involving the right atrium.

The size of the cardiovascular shadow may be studied by measuring its area, or simply by the determination of its diameters. Most commonly measured is the *transverse diameter*, which comprises the greatest distance of the right and lower left arcs from the midline (Fig. 3-26B). The size of this diameter varies from person to person but is inversely proportional to the *height* and directly proportional to the *weight* Therefore, a *height-weight index* has been devised which permits one to determine if it is within normal limits, with a 10 per cent margin of error (Table 3-4, p. 3-86).

In order to further facilitate the task and avoid complicated calculations, a *nomograph* has been devised. In order to use it, one connects by a straight line the figure of weight with that of height in order to read the corresponding normal transverse diameter; to this, 1 mm should be added for each decade of life of the patient (Table 3-3).

With the ingestion of a radiopaque substance, the *esophagus* is visualized along the midline with more or less parallel borders, except at the level of the aortic knob, here there is a depression called the "aortic notch" because it indicates the point of the aortic arch which is directed backwards.

Right Anterior Oblique Position (RAO). The cardiovascular shadow presents in this position a more elongated shadow to the right of the spinal column. Between these two struc-

TABLE 3-3 NOMOGRAPH FOR PREDICTION OF TRANSVERSE CARDIAC DIAMETER FROM HEIGHT AND WEIGHT DATA

HEIGHT
IN.: 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79
CM.: 144 148 152 156 160 164 168 172 176 180 184 188 192 196 200

WEIGHT
LBS: 96 100 104 108 112 116 120 124 128 132 136 140 144 148 152 156 160 164 168 172 176 180 184 188 192 196 200 204 208 212 216 220
KG: 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

TRANSVERSE DIAMETER MM
TELEO: 110 112 114 116 118 120 122 124 126 128 130 132 134 136 138 140 142 144 146 148 150
ORTHO: 102 104 106 108 110 112 114 116 118 120 122 124 126 128 130 132 134 136 138

SOURCE: From Ungerleidner and Gubner.

the left contour which thus forms a bridge from the upper to the lower arcs. In RAO, the *pulmonary arc* becomes salient while the lower arc reaches the chest wall and the anterior clear space *disappears. Furthermore,* there usually is a clockwise rotation of the heart which, in PA position, presents a salient middle *arc with a small aortic knob, if there* is enlargement of the left atrium, such as occurs in the case of mitral stenosis, the atrium appears on the right border as a new arc between the upper and lower (*mitral configuration,* Fig. 3-28).

LEFT ATRIAL ENLARGEMENT. This is revealed *principally in RAO by encroachment on the* retrocardiac clear space, which occurs in the middle portion only if there is a moderate enlargement, and all the way to the diaphragm in advanced cases. This is demonstrated much more clearly with visualization of the esopha-

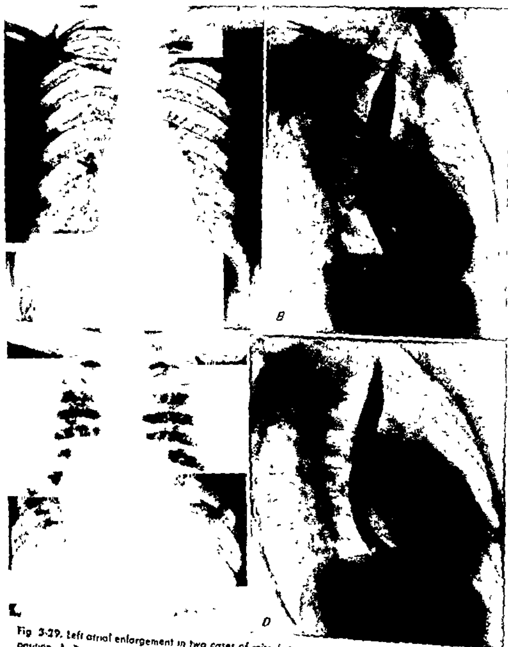


Fig 3-29. Left atrial enlargement in two cases of mitral stenosis A, C. = PA position. B, D = RAO position. A, B = moderate enlargement. C, D. = severe enlargement



Fig. 3-27. Left ventricular enlargement. A. Initial stage. B Final stage.

situs inversus and right-sided aortic arch may simply signify alteration of position, isolated dextrocardia generally coexists with other abnormalities, such as interventricular septal defect and pulmonic stenosis.

Form. The cardiovascular shadow may undergo several changes due to a greater extension or curvature of one of its normal arcs, or to the appearance of new curvatures as a result of dilatation (exclusively or predominantly) of one of the four heart chambers, or as a result of aneurysms, cysts, or tumors, or finally as a result of accumulation of fluid in the pericardial cavity or of pericardial cysts

LEFT VENTRICULAR ENLARGEMENT. Left ventricular enlargement is revealed by greater curvature of the lower arc of the left contour (*concentric hypertrophy*) or by elongation of the same arc (*enlargement of the outflow tract*). This picture may be confused with the appearance of a normal horizontal heart; however, in the case of enlargement, the picture persists during deep inspiration, a fact which is not true for a rotated heart. If, furthermore, the posterior contour of the cardiac silhouette passes *beyond* the shadow of the spinal column in LAO, this indicates an enlargement of the outflow tract. In extreme cases, the left lower arc reaches the lateral chest wall, sinks into the air chamber of the stomach, and becomes so curved that the apex is round and has the appearance of a sheep's nose (aortic insufficiency or stenosis; severe and prolonged arterial hypertension; Fig. 3-27).

RIGHT VENTRICULAR ENLARGEMENT. In its initial phase, there is an enlargement of the outflow tract which is characterized in the frontal position by a stretched middle arc of



Fig. 3-28. Right ventricular enlargement. A. Mitral stenosis (PA) B Tetralogy of Fallot (PA). C. Same as (B) in RAO.

the *left contour* which thus forms a bridge from the upper to the lower arcs. In RAO, the pulmonary arc becomes salient while the lower arc reaches the chest wall and the anterior clear space disappears. Furthermore, there usually is a clockwise rotation of the heart which, in *PA position*, presents a salient *middle* arc with a small aortic knob; if there is enlargement of the left atrium, such as occurs in the case of mitral stenosis, the atrium appears on the right border as a new arc between the upper and lower (*mitral configuration;* Fig 3-28).

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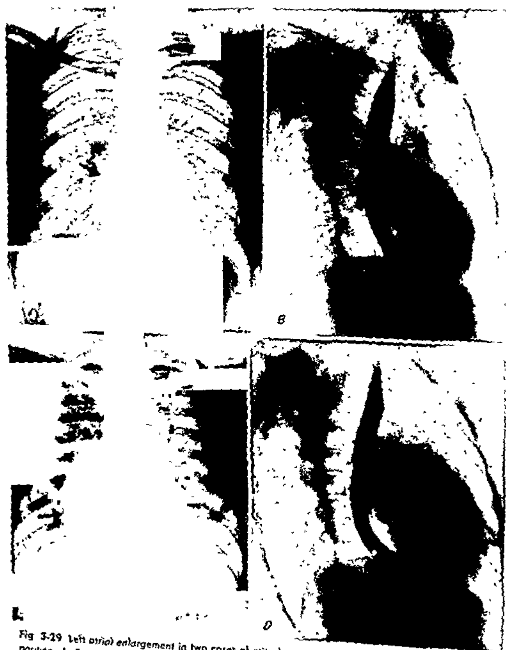


Fig 3-29 Left *atrial enlargement* in two cases of *mitral* stenosis A, C. = PA position B, D = RAO position A, B = moderate enlargement C, D. = severe enlargement.



Fig. 3-27. Left ventricular enlargement. A. Initial stage. B. Final stage.

situs inversus and right-sided aortic arch may simply signify alteration of position, isolated dextrocardia generally coexists with other abnormalities, such as interventricular septal defect and pulmonic stenosis

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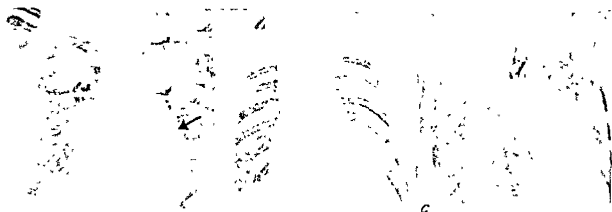


Fig. 3-28. Right ventricular enlargement. A. Mitral stenosis (PA). B Tetralogy of Fallot (PA). C. Same as (B) in RAO.

Fig 3-32. Aortic aneurysms A Aneurysm of the ascending aorta, B. Diffuse dilatation of the descending aorta

vessel An *aneurysm of the pulmonary artery* gives rise to a prominence of the middle arc on the left in the PA, and to a forward prominence of the superior arc in the RAO position, generally with great systolic expansion

CYSTS AND TUMORS Cardiac hydatid cysts and primary or secondary tumors of the myocardium are represented as *one or more new arcs* in one or more positions according to their situation, with the outstanding characteristic that they do *not* present the slightest *direct* pulsation On the other hand, *they may show transmitted pulsations.*

PERICARDIAL EFFUSION The existence of fluid in the pericardial cavity in a quantity of more than *300 to 500 ml* often produces a characteristic deformity of the cardiovascular shadow. The left and right lower arcs are more

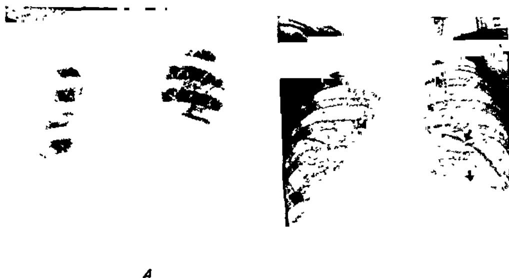


Fig. 3-33. A. Pericardial effusion. B. Hydropneumopericardium.



Fig. 3-30. Right atrial enlargement in a case of atrial septal defect

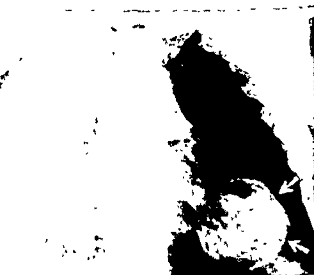
gus which, in these cases, has a characteristic backward curvature, either in its middle third or all the way to the diaphragm, according to the degree of enlargement. With marked enlargement, and more so in extreme cases, *the atrium may stand out from the contours in the PA position,* rarely on the left side and more frequently on the right, producing a third arc and even constituting the entire lower arc of the right border. Its upward expansion may encroach on the left bronchus, *enlarging the bronchial angle* and even curving it upwards with total or partial collapse of its lumen (Fig 3-29).

RIGHT ATRIAL ENLARGEMENT. This is represented in its initial stages by a greater extension and curvature of the right lower arc, better observed in LAO, especially if there is also dilatation of the auricular appendage, which becomes almost horizontal. When the condition is more advanced, there may also be posterior enlargement of the shadow with obliteration of the retrocardiac clear space in its lower part, but without dorsal displacement of the esophagus such as is seen in enlargement of the left atrium (Fig. 3-30).

A *parietal aneurysm of the heart* is revealed by a new arc at the apex or on the convexity of the left ventricle, in PA or LAO depending upon its location; this new arc has the characteristic of expansile pulsation, or remains stationary during systole in contrast to the contraction of the rest of the heart (Fig. 3-31). An *aneurysm of the ascending portion of the aorta* produces a greater curvature of the superior arc on the right, usually animated by large systolic expansions (Fig. 3-32A) in LAO, this is salient either anteriad or posteriad according to whether its implantation is toward the right or the left. An *aneurysm of the aortic arch* increases the extension and diameter of the aortic bulb; an *aneurysm of the descending aorta* is visible in the oblique positions simply as a pulsating enlargement of the body of the



A



B

Fig. 3-31. A. Ventricular aneurysm. B. Apical calcified aneurysm of the left ventricle.

during the acute stage of myocardial infarct (dynamic parietal aneurysm) and in the case of a cicatricial parietal aneurysm

Changes of Mobility. The cardiovascular shadow is not displaced toward one of the sides in the lateral positions, nor does it descend with deep inspiration, if there are dense and firm *pericardial adhesions.*

Pulmonary Vascularization. The vascularization of the lungs may be either diminished or increased, globally or partially. The reduction of the vascularization is revealed by abnormally small hilar shadows (sometimes almost absent), extremely clear pulmonary fields, and a clear aortic window. Observation of the *pulmonary markings* is of great importance in congenital heart disease, being decreased in pulmonic stenosis and tetralogy of Fallot, and increased in left-to-right shunts and the Eisenmenger syndrome

ROENTGENOGRAPHY AND ORTHODIAGRAPHY

Roentgenologically, the heart is a comparatively dense organ almost completely surrounded by radiolucent lung tissue Its structure is such as to permit delineation of various contours and densities and, with the aid of cardiac pulsations, it is possible to identify and assess the size and alterations of the individual heart chambers and of the great vessels leading to and from the heart.

Roentgenology of the heart may be properly subdivided into various techniques, among which the most useful and practical are roentgenography, roentgenoscopy (fluoroscopy) and orthodiagraphy. Roentgenogical techniques such as angiocardiography, roentgen kymography, and electrokymography will be covered elsewhere (Part 4, Chaps 7, 8), fluoroscopy, which is an integral part of the examination, has been covered in this section.

Teleoroentgenography is the taking of chest roentgenograms with the *x-ray tube* at a standard distance from the film, usually 2 *m* At such a distance, the divergent rays which delineate the borders of the cardiac shadow exaggerate its size from 4 to 12 per cent.

For the posteroanterior (PA) *view*, the patient's sternum is in contact with the film cassette The target of the roentgen tube is centered at the level of the 6th thoracic *vertebra* Synchronization of the exposure with systole or diastole may at times make a significant difference, but the most important feature in the determination of heart size is that the picture *must* be made with the diaphragm in a standard position Exposures should be made at the end of *normal expiration*, especially so since, after a deep inspiration, there is a tendency for the patient to bear down and produce the Valsalva effect which diminishes the heart size considerably.

Roentgenograms taken in the right and *left anterior oblique positions* are desirable to supplement the PA view. *Lateral views* have value because they are taken in a position that can be reproduced for serial examinations, but ordinarily they do not offer as much information as the oblique views about the size and shape of the different cardiac chambers and the aorta

For measurements in the PA view, a vertical midline is drawn approximately through the spinous processes of the dorsal vertebrae The perpendiculars from this line to the most distant points on the right and *left heart* borders are added together to constitute the *transverse diameter* (TD). The ratio between the *transverse* diameter of the heart and the transverse diameter of the thorax (*cardiothoracic ratio*), though commonly used, is inaccurate as an index of cardiac enlargement.

Tables of normal cardiac measurements and their variation with physiological limits as affected by height, weight, and age are often employed (Table 3-4). The disadvantage of prediction formulas as applied to teleoroentgenography and also to orthodiagraphy is that they do not always correctly distinguish between hearts of normal and abnormal size. *Measurements greater than the predicted normal are sometimes obtained in normal subjects while normal measurements are sometimes obtained from hearts with evident enlargement of individual chambers.* Indeed, a measurement 10 per cent greater than the predicted figure may occasionally be obtained in a normal heart. This lessens the value of the measurement in the borderline group, where a decisive answer would be most desirable, but despite this, measurements have a certain screening value. There still may be borderline cases in which neither measurement, roentgenoscopy, nor other roentgenographic techniques will offer the decisive answer as to whether or not enlargement is present.

extensive and curved, the cardiophrenic angles become more acute, and the whole silhouette resembles a *water bag* with a short, narrow neck, the whole structure becomes wide when the patient lies in a recumbent position (Fig. 3-33). In RAO, the lowermost portion of the retrocardiac space is usually obliterated early.

PERICARDIAL DIVERTICULA. These appear as *new arcs in the cardiac contour, semilunar or* ovoid in shape and presenting transmitted pulsations.

Size. The size of the cardiovascular shadow *may be diminished or increased, with preservation* of its form or with some of the above-mentioned deformities. Marked deviation from the normal values may be recognized at first sight with only a little experience, but lesser variations must be established by using the *height-weight nomogram,* remembering that deviations of 10 per cent or less have no significance if the rest of the physical examination does not justify a diagnosis of a pathological condition. For this reason, *more diagnostic importance is attributed to deformity and more prognostic value to enlargement,* the prognosis being gradually worse in direct proportion to the degree of enlargement

A *reduction in size* is not evidence of organic heart disease, but reveals a *constitutional peculiarity* ("drop heart") or the result of *chronic malnutrition with physical inactivity* (Addison's disease, consumption, cachexia) Conversely, an *increase in size* is always evidence of organic heart disease, usually irreversible

An increase in size with preservation in form of the cardiac shadow may be observed in *diffuse myocardial disease,* such as cardiac beriberi, rheumatic carditis, anemia, and thyrotoxicosis.

An increase in the size of the shadow of the large vessels at the base may give rise to several pictures depending on the cause.

1 Prominence of the right border with preservation of its form, due to dilatation of the superior vena cava, in *right heart failure*

2 Prominence of the superior arc of the right border with a curve toward the right, *due to dilatation of the ascending or transverse aorta* (hypertension, syphilis, arteriosclerosis) *Visualization of the descending* aorta may even cause the appearance of a new arc beyond the middle arc of the left border; in such cases, the aortic window in LAO is seen open and the descending aorta passes beyond the vertebral column.

3 A prominent middle arc with an extensive hilar shadow and an obliterated aortic window, due to *dilatation of the pulmonary artery and its branches* because of hypertension of the lesser circuit.

Density. Instead of the uniform density of the cardiovascular shadow, there may be linear increases in density in the cardiac contour (*pericardial calcification*), aortic knob (*aortic calcification*), *or within the cardiac shadow* (*valvular calcification*). True plaques, such as those found in a *calcified infarct* may appear, rather than linear densities.

A rounded, uniform slight increase in the cardiac shadow at the base, which may pass beyond the right border at the level of the hilus is due to an increase in the size of the left atrium

Pulsations. Pulsations of the borders may be slight or even absent during fluoroscopy (*quiet heart*), although they appear in roentgen kymography. They may be exaggerated (locally or globally), as well as altered, so that there may be a systolic distention instead of the normal contraction (*paradoxical pulsation*).

Pulsations are *uniformly diminished,* or even abolished, in *constrictive pericarditis, marked cardiac enlargement* (more so if there *is heart* failure), and *pericardial effusion* In the latter case, the diminution of pulsations is noted only in the lower portion of the contours, since they are normal over the aortic knob. Unfortunately this sign, which has great value, is not always completely reliable In certain cases, concurrent myocarditis or heart failure weakens the aortic pulsations.

Pulsations are diminished or even abolished locally in *myocardial infarct* and *mediastinopericarditis,* although in the former instance there may be "paradoxical pulsations"

The pulsations are of great amplitude in small hearts and in insufficiency of the semilunar valves As may be expected, the increase is found over the borders of the left ventricle and aorta in *aortic insufficiency,* and over those of the right ventricle, pulmonary artery, and its branches (*hilar dance*) in *pulmonic insufficiency*

A *systolic expansion,* or paradoxical pulsation, in a localized zone, can be found both

during the acute stage of myocardial infarct (dynamic parietal aneurysm) and in the case of a cicatricial parietal aneurysm

Changes of Mobility. The cardiovascular shadow is not displaced toward one of the sides in the lateral positions, nor does it descend with deep inspiration, if there are dense and firm *pericardial adhesions*

Pulmonary Vascularization. The vascularization of the lungs may be either diminished or increased, globally or partially The reduction of the vascularization is revealed by abnormally small hilar shadows (sometimes almost absent), extremely clear pulmonary fields, and a clear aortic window. Observation of the *pulmonary markings* is of great importance in congenital heart disease, being decreased in pulmonic stenosis and tetralogy of Fallot, and increased in left-to-right shunts and the Eisenmenger syndrome

ROENTGENOGRAPHY AND ORTHODIAGRAPHY

Roentgenologically, the heart is a comparatively dense organ almost completely surrounded by radiolucent lung tissue Its structure is such as to permit delineation of various contours and densities and, with the aid of cardiac pulsations, it is possible to identify and assess the size and alterations of the individual heart chambers and of the great vessels leading to and from the heart.

Roentgenology of the heart may be properly subdivided into various techniques, among which the most useful and practical are roentgenography, roentgenoscopy (fluoroscopy) and orthodiagraphy. Roentgenogical techniques such as angiocardiography, roentgen kymography, and electrokymography will be covered elsewhere (Part 4, Chaps 7, 8), fluoroscopy, which is an integral part of the examination, has been covered in this section

Teleoroentgenography is the taking of chest roentgenograms with the x-ray tube at a standard distance from the film, usually 2 m At such a distance, the divergent rays which delineate the borders of the cardiac shadow exaggerate its size from 4 to 12 per cent.

For the *posteroantenor* (PA) view, the patient's sternum is in contact with the film cassette The target of the roentgen tube is centered at the level of the 6th thoracic vertebra Synchronization of the exposure with systole or diastole may at times make a significant difference, but the most important feature in the determination of heart size is that the picture must be made with the diaphragm in a standard position Exposures should be made at the end of *normal expiration*, especially so since, after a deep inspiration, there is a tendency for the patient to bear down and produce the Valsalva effect which diminishes the heart size considerably

Roentgenograms taken in the *right* and *left anterior oblique positions* are desirable to supplement the PA view. *Lateral views* have value because they are taken in a position that can be reproduced for serial examinations, but ordinarily they do not offer as much information as the oblique views about the size and shape of the different cardiac chambers and the aorta

For measurements in the PA view, a vertical midline is drawn approximately through the spinous processes of the dorsal vertebrae The perpendiculars from this line to the most distant points on the right and left heart borders are added together to constitute the *transverse diameter* (TD) The ratio between the transverse diameter of the heart and the transverse diameter of the thorax (*cardiothoracic ratio*), though commonly used, is inaccurate as an index of cardiac enlargement

Tables of normal cardiac measurements and their variation with physiological limits as affected by height, weight, and age are often employed (Table 3-4) The disadvantage of prediction formulas as applied to teleoroentgenography and also to orthodiagraphy is that they do not always correctly distinguish between hearts of normal and abnormal size. *Measurements greater than the predicted normal are sometimes obtained in normal subjects while normal measurements are sometimes obtained from hearts with evident enlargement of individual chambers* Indeed, a measurement 10 per cent greater than the predicted figure may occasionally be obtained in a normal heart This lessens the value of the measurement in the borderline group, where a decisive answer would be most desirable; but despite this, measurements have a certain screening value There still may be borderline cases in which neither measurement, roentgenoscopy, nor other roentgenographic techniques will offer the decisive answer as to whether or not enlargement is present.

TABLE 3-4 PREDICTION OF AVERAGE NORMAL ORTHODIAGRAPHIC MEASUREMENTS OF THE TRANSVERSE DIAMETER OF THE HEART *

(Predicted TD = +0.1094 × A − 0.1941 × H + 0.8179 × W + 95.8625) †

I				*II*			
Stature		*Area, cm²*	*Transverse diameter, mm*	*Weight*		*Area, cm²*	*Transverse diameter, mm*
Centimeters	*Inches*			*Kilograms*	*Pounds*		
150	59	66.7	66.74	50	110	17.00	40.90
151		67.57	66.55	51	112.2	17.34	41.71
152	60	68.44	66.36	52	114.4	17.68	42.53
153		69.31	66.16	53	116.6	18.02	43.35
154		70.18	65.97	54	118.8	18.36	44.17
155	61	71.05	65.77	55	121	18.70	44.98
156		71.92	65.58	56	123.2	19.04	45.80
157		72.79	65.39	57	125.4	19.38	46.62
158	62	73.66	65.19	58	127.6	19.72	47.44
159		74.53	65.00	59	129.8	20.06	48.26
160	63	75.40	64.80	60	132	20.40	49.07
161		76.27	64.61	61	134.2	20.74	49.89
162		77.14	64.42	62	136.4	21.08	50.71
163	64	78.01	64.22	63	138.6	21.42	51.53
164		78.88	64.03	64	140.8	21.76	52.35
165	65	79.75	63.83	65	143	22.10	53.16
166		80.62	63.64	66	145.2	22.44	53.98
167		81.49	63.45	67	147.4	22.78	54.80
168	66	82.36	63.25	68	149.6	23.12	55.62
169		83.23	63.06	69	151.8	23.46	56.44
170	67	84.10	62.86	70	154	23.80	57.25
171		84.97	62.67	71	156.2	24.14	58.07
172		85.84	62.47	72	158.4	24.48	58.89
173	68	86.71	62.28	73	160.6	24.82	59.71
174		87.58	62.09	74	162.8	25.16	60.52
175	69	88.45	61.89	75	165	25.50	61.34
176		89.32	61.70	76	167.2	25.84	62.16
177		90.19	61.50	77	169.4	26.18	62.98
178	70	91.06	61.31	78	171.6	26.52	63.80
179		91.93	61.12	79	173.8	26.86	64.61
180	71	92.80	60.92	80	176	27.20	65.43
181		93.67	60.73	81	178.2	27.54	66.25
182		94.54	60.53	82	180.4	27.88	67.07
183	72	95.41	60.34	83	182.6	28.22	67.89
184		96.28	60.15	84	184.8	28.56	68.70
185	73	97.15	59.95	85	187	28.90	69.52
186		98.02	59.76	86	189.2	29.24	70.34
187		98.89	59.56	87	191.4	29.58	71.16
188	74	99.76	59.37	88	193.6	29.92	71.98
189		100.63	59.18	89	195.8	30.26	72.79
190		101.50	58.98	90	198	30.60	73.61
191	75	102.37	58.79	91	200.2	30.94	74.43
192		103.24	58.59	92	202.4	31.28	75.25
193	76	104.11	58.40	93	204.6	31.62	76.06
194		104.98	58.21	94	206.8	31.96	76.88
195		105.85	58.01	95	209	32.30	77.70
196	77	106.72	57.82	96	211.2	32.64	78.52
197		107.59	57.62	97	213.4	32.98	79.34
198	78	108.46	57.43	98	215.6	33.32	80.15
199		109.39	57.23	99	217.8	33.66	80.97
200	79	110.20	57.04	100	220	34.00	81.79

* The figures of this table are valid for orthodiagrams and for male subjects The hearts of female subjects of the same stature, weight, and age are slightly smaller in size Bainton has suggested that 0 8 cm be subtracted for TD of female

TD figure for stature to TD figure for height, 6 ft, weight, 187 lb, age, 50 →

wc
13

The chief use of measurements is for comparison of *serial roentgenograms* in each individual case This is particularly important when cardiac enlargement is present because the degree of variation in heart size is useful in following the progress of the disease On the other hand, it is more important to ascertain which chambers are involved in the enlargement, and to what degree Such information cannot be obtained by measurement, and probably is best determined by roentgenoscopy.

Orthodiagraphy utilizes the *central parallel rays* to outline cardiac contours, enabling the examiner to make tracings closely approximating in size and shape the outline of the heart in the plane under observation The outline of the diaphragm and of the median line are similarly drawn Tracings of the lower contours of the heart and the upper contours at the base should not be attempted, because the opaque infradiaphragmatic structures and vertebral column obscure the cardiac borders The transverse diameter of the surface area is compared with prediction formulas based on age, height, and weight to determine the presence or absence of *enlargement* (Table 3-4). Technically, orthodiagraphy is subject to but slight error in skilled hands. The interpretation of the tracing is subject to the same difficulties that have been discussed under "teleoroentgenography" Several types of apparatus are available or can be improvised for orthodiagraphy, their description will be omitted for the sake of brevity.

PA View: Normal Heart Contours. The outline of the margins of the heart can be divided into portions or curves, each corresponding to an individual heart chamber or great vessel (Fig. 3-34B) In the PA view, on the right side, the curves of the *ascending aorta* and the *right atrium* usually can be differentiated On deep inspiration, a small triangular shadow sometimes can be seen between the diaphragm and the lower contour of the right atrium. It is caused by the *inferior vena cava* or *hepatic veins* and is not to be mistaken for pleuropericardial adhesions Above the arch, the vertical shadow of the superior vena cava often is seen to extend parallel and close to the spine.

On the left side, reading from the top down are *the aortic knob, the pulmonary artery,* and *the left ventricle.* On electrokymography, *the auricular appendage of the left atrium* can be identified at times between the pulmonary artery and the left ventricle, but in normal hearts it rarely projects sufficiently to form a distinct contour of its own.

Since the pulmonary artery pulsates outward in systole while the left *ventricle* pulsates in an inward direction, a *point of opposite pulsations* can be indicated. The upper margin of the left ventricle can be said to begin at this point of opposite pulsations, or as high as definite left ventricular pulsations can be [illegible]

[illegible] or pulmonary artery segment The inferior contour of the heart, even when viewed in deep inspiration, cannot ordinarily be seen below the dome of the left side of the diaphragm However, it can be visualized through the use of Seidlitz powders or carbonated beverages.

In the left cardiodiaphragmatic angle, a tri-

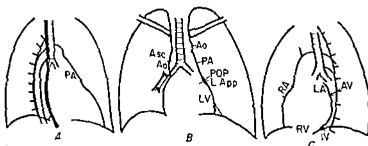


Fig 3-34 A Normal heart, RAO position Note the gradual descending curve of the barium-filled esophagus with its concavity anteriorly On deep *inspiration* this normally should straighten out B Normal *heart*, PA position *LV*, left ventricle, *PA*, pulmonary artery trunk; *Ao*, aorta; *POP*, point of opposite pulsations, *L App*, left auricular *appendage*. Note that the right bronchus separates the *descending* branch of the right pulmonary artery from the right cardiac contour. Thus, its width can be measured. C. Normal heart, LAO position: *RA*, right atrium, *LA*, left atrium, *RV*, right ventricle. Arrows point to *AV* (atrioventricular sulcus), *IV* (interventricular groove).

angular shadow less dense than that of the left ventricle and the diaphragm is frequently seen, formed by epicardial fat.

Right Anterior Oblique (RAO) Position. The *anterior contour* is formed from above down by the ascending aorta, the pulmonary artery, and either the right or left ventricle, depending upon the degree of rotation (Fig. 3-34A). The *ascending aorta* is continuous above with a foreshortened view of the transverse portion of the aortic arch The *descending aorta* often may be noted between the posterior surface of the heart and the vertebral column It is best seen during inspiration, and especially well in subjects with dorsal kyphosis or pulmonary emphysema. The *posterior contour* of the heart is formed from below up by *the inferior vena cava, the right atrium,* and *the left atrium.* Ordinarily one cannot differentiate between the two atria unless either of these chambers is enlarged The air column of the trachea and the right bronchus can be seen between the shadow of the descending portion of the aortic arch and the upper posterior outline of the heart The esophagus lies between the anterior surface of the descending aorta and the posterior surface of the heart When the esophagus is filled with a medium-thick barium paste, its downward course is seen to be essentially vertical, or to have a shallow curve posteriorly. The continuity of the anterior contour of the barium-filled esophagus is broken by the normal indentation of the aortic arch and, lower down, by the right bronchus The left atrial impression on the barium-filled esophagus is an extremely shallow arc; this arc tends to become a vertical line on deep inspiration

Left Anterior Oblique (LAO) Position. The *anterior outline* is formed from below upwards by the right ventricle, the right atrium and its appendage, and the ascending aorta (Fig 3-34C). The contours of the aorta and that of the right atrium are essentially vertical, while the intervening contour of the right auricular appendage slopes obliquely towards the aorta

The shallow anterior curvature of *the ascending aorta* can be further reduced on inspiration. The ascending limb of *the aortic arch* is seen to curve upwards and posteriorly, continuous with the transverse portion of the arch. This in turn is seen to curve downwards into the descending limb of the arch and *the thoracic aorta;* the latter partially overlaps the dense area of the vertebral column

The *posterior contour* of the heart is formed by *the left ventricle* below and *the left atrium* above. A shallow indentation, the *atrioventricular groove,* may be seen to separate the two. At or near the junction of the left ventricle with the diaphragm, an indentation may be observed which is especially evident in systole during deep inspiration. This is the *interventricular groove,* and the indentation is due to the contraction of the interventricular septum This contraction has an upward movement of its own, independent of the contractions of the chambers to either side of it, but taking place at the same time.

The bifurcation of the trachea is seen within and below the shadow of the aortic arch. The right bronchus appears foreshortened, while the course of the left bronchus is more vertical than horizontal. The *left branch of the pulmonary artery* may be identified as a shadow, less dense and narrower than the aorta, arching over the left main bronchus, having its origin in a dense area within the heart shadow (pulmonary artery bifurcation seen on end).

The size and shape of the cardiac shadow is greatly influenced by the position occupied by the diaphragm

In *horizontal hearts* occurring in hypersthenic individuals, the heart lies horizontally on an elevated diaphragm, the roentgenological apex of the heart is displaced to the left, and the lower portion of the left contour is often obscured by the diaphragm. Relatively more of the contour of the left ventricle and less of the pulmonary artery segment can be seen. Likewise, in the oblique position, the right ventricular surface resting on the diaphragm is broadened, the right auricular segment is also seemingly elongated, and the aortic segment curves anteriorly. On deep inspiration, the true dimensions of these segments may become apparent Under such circumstances, the heart in inspiration will assume the contours of the sthenic heart or heart of intermediate shape The contours described as normal contours apply here

The *vertical heart* occurs as a rule in tall, thin individuals, and appears long and narrow. In extreme forms it appears suspended, almost teardrop or pear-shaped The pulmonary artery forms a large part of the contour below the

aortic knob, in the PA position. In the RAO position, the pulmonary artery segment is prominent. In asthenic individuals this prominence does not necessarily indicate enlargement of the right ventricular outflow portion In the LAO position, the right ventricular portion resting on the diaphragm is relatively small, the left ventricle appears posterior to it, as if suspended from the right ventricle. The interventricular groove is likely to be visualized more frequently in the vertical heart than in other heart shapes However, on expiration the cardiac contours in all views approach the intermediate or the sthenic heart.

In *infants*, the shape of the heart is usually *globular*, and in *children* it is frequently so It is centrally located, and its borders reach about equally far to the left and to the right. Between the extremes of the horizontal and the vertical hearts is the intermediate heart in sthenic individuals The relative lengths of the pulmonary artery segment and that of the left ventricle *may be more or less equal*

LEFT VENTRICLE

The left ventricle can be subdivided anatomically and functionally into two portions, the *inflow* and *outflow tracts* or *portions* The inner wall of the outflow portion is relatively smooth as compared to the more trabeculated inflow portion of the chamber lying below and lateral to the mitral orifice The outflow portion, for the purposes of this discussion, represents the length of the left ventricle from the apex of this chamber to the aortic valve This portion enlarges early in the course of left ventricular enlargement Its roentgenological counterpart is the increase in length of the left ventricular segment as noted in the PA position. This increased length may be recognized either in terms of downward extension of the left ventricular segment or by increased rounding of the left ventricular contour. *Elongation by downward extension* is relatively uncommon, and rather difficult to determine since the density of the infradiaphragmatic structures tends to obscure the left ventricle pushing down the central portion of the diaphragm Filling the stomach with a carbonated beverage will help at times to visualize left ventricular elongation in such instances; at other times accumulations of gas in the *transverse colon* or in the splenic flexure may also be helpful (Fig 3-35).

Elongation by rounding is by far the more common way of expressing *the increased length of the left ventricular outflow tract* This increased rounding must be looked for in the upper half of the left ventricular contour, since the lower half of the left ventricular contour, even when visualized within the epicardial apical fat pad, generally is rounded, even when there is no left ventricular enlargement

Inflow tract enlargement, the representation of increased length or depth extending from the mitral valve to the apex of this chamber, is first and best noted in the LAO position. Here, the increase in length is manifested either by increased rounding, or by the displacement of the interventricular groove down-

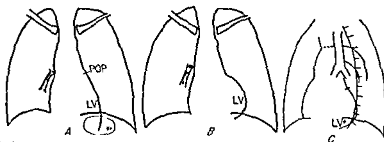


Fig 3-35. A Left *ventricular enlargement*, uncommon type Enlargement by elongation with the lower portion of the contour seen within the infradiaphragmatic *density*, here illuminated by an accumulation of gas in the stomach air bubble B. Slight to moderate left ventricular enlargement here the elongation of the left ventricular contour is manifested by an increase in rounding below the point of opposite *pulsations* C. Left ventricular enlargement, slight to moderate grade, LAO position. Increase in length and rounding displacing the interventricular *groove* downwards and forwards. Attempts to ascertain *if left* ventricular enlargement is present by estimating angles of clearance are erroneous except when the degree of enlargement is marked or massive

angular shadow less dense than that of the left ventricle and the diaphragm is frequently seen, formed by epicardial fat.

Right Anterior Oblique (RAO) Position. The *anterior contour* is formed from above down by the ascending aorta, the pulmonary artery, and either the right or left ventricle, depending upon the degree of rotation (Fig. 3-34A). The *ascending aorta* is continuous above with a foreshortened view of the transverse portion of the aortic arch The *descending aorta* often may be noted between the posterior surface of the heart and the vertebral column It is best seen during inspiration, and especially well in subjects with dorsal kyphosis or pulmonary emphysema. The *posterior contour* of the heart is formed from below up by *the inferior vena cava, the right atrium,* and *the left atrium.* Ordinarily one cannot differentiate between the two atria unless either of these chambers is enlarged The air column of the trachea and the right bronchus can be seen between the shadow of the descending portion of the aortic arch and the upper posterior outline of the heart. The esophagus lies between the anterior surface of the descending aorta and the posterior surface of the heart When the esophagus is filled with a medium-thick barium paste, its downward course is seen to be essentially vertical, or to have a shallow curve posteriorly The continuity of the anterior contour of the barium-filled esophagus is broken by the normal indentation of the aortic arch and, lower down, by the right bronchus. The left atrial impression on the barium-filled esophagus is an extremely shallow arc, this arc tends to become a vertical line on deep inspiration

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In *horizontal hearts* occurring in hypersthenic individuals, the heart lies horizontally on an elevated diaphragm, the roentgenological apex of the heart is displaced to the left, and the lower portion of the left contour is often obscured by the diaphragm. Relatively more of the contour of the left ventricle and less of the pulmonary artery segment can be seen Likewise, in the oblique position, the right ventricular surface resting on the diaphragm is broadened, the right auricular segment is also seemingly elongated, and the aortic segment curves anteriorly On deep inspiration, the true dimensions of these segments may become apparent Under such circumstances, the heart in inspiration will assume the contours of the sthenic heart or heart of intermediate shape The contours described as normal contours apply here

The *vertical heart* occurs as a rule in tall, thin individuals, and appears long and narrow. In extreme forms it appears suspended, almost teardrop or pear-shaped The pulmonary artery forms a large part of the contour below the

greater degree of left atrial enlargement suggests or confirms the diagnosis.

Marked to Excessive Enlargement. The most common causes for such enlargement are *aortic insufficiency, combined aortic stenosis and insufficiency,* or *hypertension.* Occasionally patients with *myocardial infarction(s)* develop marked enlargement too and, in such patients, one is tempted to think of an antecedent hypertension as an added causative factor, but it is often difficult to corroborate such a contention. When massive left ventricular enlargement is present in the absence of the signs of valvular heart disease, antecedent hypertension is often postulated. This may be confirmed by a more thorough search of the past records of the patient, by the demonstration of dilatation of the ascending aorta or by finding arterial narrowing and arteriovenous compression when the fundi are examined.

Ventricular Aneurysm. Ventricular aneurysm is the commonly used term applied to a localized bulge in the ventricular wall. It is usually due to a healed, or almost healed, area of myocardial damage wherein the thinned portion of the wall bulges. The most frequent site is *at the apex* of the left ventricle and is most apparent in deep inspiration (Fig. 3-36). However, if inspiration is prolonged, the Valsalva effect supervenes and the bulge may diminish or even disappear. Other sites of bulging are high on the lateral wall and on the posterior wall. Examination in the oblique positions, as well as in the posteroanterior, is necessary. Increase in density due to layers of *intraventricular (mural) thrombi, incisuras,*[1] pericardial adhesions and, on rare occasions, calcified areas, may be helpful in the recognition of the affected site. Thinning of almost the entire lateral wall of the left ventricle occasionally occurs. It is difficult to differentiate this from massive left ventricular enlargement.

LEFT ATRIUM

For the most part, the left atrium is a smoothly lined chamber, while its smaller portion, *the auricular appendage,* is trabeculated. It lies posteriorly below the tracheal bifurcation, anterior to and almost in direct contact with the esophagus. In the RAO position, it is virtually impossible to differentiate between the posterior contours of the left and right atria except when one of these chambers is enlarged. In normal individuals and in the PA position, the tip of the left auricular appendage generally helps to form a part of the left contour, between the pulmonary artery above and the left ventricle below. It seldom projects sufficiently in normal individuals to form a definite contour of its own.

[1] "Incisura" denotes the junction of the arcs between involved and uninvolved portions of the left ventricle.

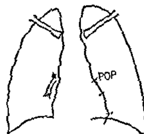


Fig. 3-36. Ventricular aneurysm (left ventricular bulge) usually found at the apex, and best picked up by fluoroscopy or electrokymography when paradoxical pulsations are evident. Upper arrow points inwards in systole, lower arrow points outwards during the same phase of the cardiac cycle.

Enlargement of the Left Atrium. This is first and best recognized by its encroachment on the retrocardiac space (Fig. 3-37). It is visualized in the RAO position as an arched cardiac density projecting towards the spine, situated in the midportion of the posterior cardiac contour below the tracheal bifurcation. The extent of this horizontal enlargement can be inferred by the degree of compression or displacement of the barium-filled esophagus posteriorly. One must be sure, however, to distinguish such displacement from that due to the esophagus being pulled to the left and backwards by its adhesions to an elongated aortic arch, or to other mediastinal structures. Since such an esophagus is displaced from its usual intimate relationship to the posterior surface of the heart, it can no longer be used as a guide to left atrial enlargement.

Superiorly, the left atrium lies in relation to the bifurcation of the trachea and the main bronchi. *Vertical or upward enlargement* of the left atrium can be observed in its successive stages in the LAO position, first by the disappearance of the air space below the left main bronchus, then by a spreading of the angle between the two main bronchi. Later, there is compression or displacement of the left bronchus upwards and to the left.

ward and anteriorly. Extension posteriorly, overlapping the spine, as well as extension of the left ventricular outline laterally in the PA position, occurs later in the course of left ventricular enlargement.

Ordinarily, normal left ventricular length varies with the type of heart, be it vertical, horizontal, or intermediate Left ventricular lengths along the lateral contour in the PA view vary from 2 or 2½ in. in vertical hearts to as much as 4 or 4½ in. in horizontal hearts, and even more in large individuals. Normal lengths of the inflow portion, as measured between the atrioventricular and the interventricular grooves, measure pretty much the same as in the outflow portion

There is no way to differentiate between various types of left ventricular enlargement. In other words, slight or moderate left ventricular enlargement in hypertension, aortic stenosis, mitral insufficiency, coarctation, or secondary to myocardial infarction, will present similar outlines Slight left ventricular enlargement will be best seen in the PA position while moderate degrees of enlargement will be noted in both the PA and LAO positions.

In the author's viewpoint, *typical configurations are often absent and, when present, assume clinical connotations which may be erroneous.* For instance, a so-called "mitral" shape may be the result of atrial septal defect, chronic pulmonary disease, or thyrotoxicosis The mere mention of "mitralization" may be a serious cause of diagnostic errors Estimation of the degree of individual chamber enlargement permits a dynamic or physiological evaluation of what has occurred, and often the sequence of involvement Such an estimate may correlate with the clinical diagnosis, and, if it does not so correlate, then a reevaluation of the clinical and roentgenological factors is indicated

Enlargement of a cardiac chamber is not a specific sign of any clinical disorder. It is only the manifestation of that chamber's dilatation and hypertrophy secondary to disease and to the increased demands put upon it, relative to its capacity to meet such needs Chamber enlargements differ only quantitatively, not qualitatively. Moderate left ventricular enlargement is the same in size and shape in hypertension as it is in aortic insufficiency or mitral insufficiency.

Absence of Enlargement. The left ventricle is characteristically small in *mitral stenosis* It is frequently displaced to the left by enlargement of the right ventricle and also displaced posteriorly by rotation of the heart on its vertical axis. Such displacement may give the illusion of left ventricular enlargement.

The left ventricle is not enlarged in uncomplicated *coronary heart disease* but may be enlarged slightly, moderately, or even markedly, weeks or months after an *acute myocardial infarction*, even in the absence of significant manifestations of heart failure.

Slight or Moderate Enlargement. Such enlargement is frequently present in systemic hypertension (particularly in women), aortic insufficiency, aortic stenosis, and also in mitral insufficiency. In the transient or labile stages of *hypertension*, the left ventricle is rarely enlarged. When hypertension is persistent, there may be only rounding of the upper left ventricular contour without an actual increase in chamber size, due to concentric hypertrophy, or the left ventricle may be enlarged. In hypertension, elongation and dilatation of the ascending aorta, visualized best in the LAO position by an increased curvature projecting anteriorly, occurs much more frequently than left ventricular enlargement or concentric hypertrophy

All grades of left ventricular enlargement may be encountered with *aortic insufficiency* (rheumatic, syphilitic, or due to a bicuspid aortic valve) When the pulse pressure is normal, the left ventricle is usually not enlarged, and if such enlargement is present, another causative agent for this enlargement should be sought When the pulse pressure is high (except for that caused by the nonelastic, rigid aorta of arteriosclerosis, or associated with a concomitant thyrotoxicosis), the left ventricular and aortic pulsations are considerably increased

The left ventricle is usually only slightly or moderately enlarged in *aortic stenosis* When massive enlargement occurs, it is likely to be due to associated aortic insufficiency, coronary arterial disease, mitral insufficiency, or hypertension

The left ventricle is only slightly or moderately enlarged in *mitral insufficiency* uncomplicated by aortic valvular disease or other cause for left ventricular enlargement. This grade of enlargement with a disproportionately

RIGHT VENTRICLE

This chamber for the most part lies on the diaphragm with the right atrium to its right and the left ventricle to its left. Like the left ventricle, it can conveniently be divided into two portions. the outflow portion, representing its height, the inflow portion, its depth. Indeed, the upper portion of the right ventricle, particularly the portion immediately below the pulmonic valve, is smooth so as to facilitate blood flow through this portion, in comparison with the trabeculated inflow tract or portion. The value of dividing the right ventricle into its two components, *the outflow* and *the inflow tracts*, lies in the observation that early enlargement appears as an increase in length of the outflow tract (from the apex of the right ventricle to the pulmonic valve ring), later on, in the course of further enlargement of this chamber, the outflow tract (from the apex of the ventricle to the annulus of the tricuspid valve) also becomes longer.

Enlargement of the Right Ventricle. The roentgenological methods of determining such enlargements unfortunately are indirect, rather than direct, since the border of the right ventricle does not form the contour of the cardiac shadow in the PA position, it is possible, however, to see the junction of the right atrium and ventricle, just above the diaphragm, in the PA and LAO positions. With slight degrees of rotation into the RAO position, the anterior surface of the right ventricle often is border-forming, but usually it cannot be differentiated from the contour of the left ventricle, the diaphragmatic contour is lost in the opacity of the infradiaphragmatic structures. However, certain inferences are valuable and, on the whole, reliable. Early right ventricular enlargement, associated with elongation of the outflow tract, is usually associated with dilatation of the pulmonary artery. Of course, this does not hold true in congenital heart diseases with pulmonic stenosis, persistent truncus arteriosus, or pseudotruncus arteriosus. The prominence of the pulmonary artery, in the PA as well as in the RAO positions, supplemented by the clockwise rotation of the heart on its vertical axis (as viewed from below), due to disproportionate work and hypertrophy of the right ventricle as compared to the left, cause straightening or bulge of the left upper cardiac contour in the PA view, and a bulge into the retrosternal space in the RAO position. Other effects of rotation are: diminution in size or prominence of the aortic knob, early appearance of the left atrium on the right cardiac contour in the PA position, and displacement of the left atrial portion of the barium-filled esophagus to the right in the PA position.

Later, in the course of right ventricular enlargement, there is an enlargement of the inflow tract, or an increase in depth. This is best seen in the LAO position. In this position, the diaphragmatic portion of the heart, chiefly the right ventricle, increases in length, displacing the interventricular groove posteriorly and craniad. During deep inspiration, the diaphragmatic border remains elongated instead of diminished, as it does in the normally horizontal heart. The bulge of the anterior contour towards the anterior chest wall is increased. A valuable inferential sign of right ventricular inflow tract enlargement is the concomitant demonstration of right atrial enlargement. Such enlargement would hardly occur without simultaneous enlargement of the right ventricle, except in the presence of tricuspid stenosis or atresia. Marked enlargement of the outflow and inflow portions of the right ventricle may occur without enlargement to the right in the PA view.

Slight or Moderate Right Ventricular Enlargement. Dilatation of the trunk and of the primary and secondary branches of the pulmonary artery, and also enlargement of the outflow tract of the right ventricle, are characteristic of pulmonary hypertension (of moderate or long duration) due to pulmonary or mitral valvular disease, or secondary to left ventricular failure. In children with congenital heart disease, increased contact of the cardiac shadow with that of the sternum in lateral views is reliable evidence for right ventricular enlargement.

Marked Right Ventricular Enlargement. Such enlargement is rather common in chronic rheumatic mitral valvular disease with stenosis, insufficiency, or both, with or without evidence of right ventricular failure (neck-vein distention, hepatic enlargement, edema). When marked, right ventricular enlargement is commonly associated with manifestations of right ventricular failure. In chronic pulmonary heart disease, the demonstration of inflow tract en-

ENLARGEMENT TOWARDS THE RIGHT. Enlargement of the left atrium may extend far enough to the right to appear in the middle portion of the *right* contour of the heart in the PA position. Then there may be two more or less distinct curves, the lower being the right atrium, and the upper the left atrium superimposed on the right. Not infrequently the density of the body of the left atrium is visualized within the upper central portion of the heart when films are overexposed. Rotation of the heart associated with right ventricular enlargement accentuates the displacement of the left atrium towards the right.

ENLARGEMENT TOWARDS THE LEFT. Enlargement of the left appendage does not appear on the left cardiac border at an early stage of its enlargement since usually it is obscured by coexisting enlargement of the pulmonary artery. Later, a segment of the greatly enlarged left appendage may extend further to the left than the pulmonary artery and form a recognizable contour of its own On fluoroscopy or kymography it may be identified by characteristic atrial wavelike pulsations when sinus rhythm is present

No Left Atrial Enlargement. The left atrium may not be at all enlarged with mitral stenosis (though this is infrequent), and characteristically there is no enlargement with heart disease due to pulmonary hypertension caused by pulmonary disease.

Slight to Moderate Left Atrial Enlargement. Such enlargement is frequent in mitral valvular disease. Here, the degree of enlargement is proportionately greater than that of the left ventricle. Left atrial enlargement is often present with left ventricular failure, when the grade of enlargement is less than that of the ventricle. Slight grades of left atrial enlargement are often present in myocardial infarction, even when the left ventricle is not demonstrably enlarged. Slight grades of left atrial enlargement are also present in certain types of congenital heart disease such as patent ductus arteriosus, ventricular septal defect, and tricuspid stenosis.

Marked to Excessive Left Atrial Enlargement. Giant left atria appearing on the left as well as the right cardiac contours in the PA position, extending far back into the retrocardiac space, and frequently elevating the left main bronchus, are characteristically found in mitral valvular disease: stenosis as well as insufficiency. Calcification of the annulus fibrosus ordinarily is not necessarily associated with left atrial enlargement.

Moderate to marked grades of left atrial enlargement are commonly noted with left ventricular enlargement and failure. Characteristically, the grade of enlargement is less than that of the left ventricle, though at times these differential grades of enlargement are difficult to determine

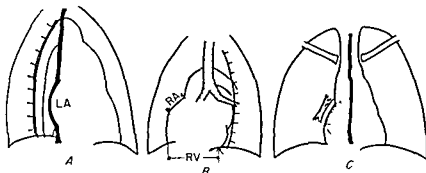


Fig. 3-37. A Slight to moderate left atrial enlargement compressing and displacing the barium-filled esophagus posteriorly. Note also the bulge of the pulmonary artery trunk anteriorly into the anterior mediastinal space The degree of bulging generally correlates well with the degree of right ventricular enlargement B. LAO position: RA, right atrium; RV, right ventricle. Increased depth of the right ventricle is present. The right atrial segment is elongated. Left ventricular enlargement is seen. The left atrium elevates and to some degree compresses the distal portion of the left main bronchus. C. Left atrial enlargement in the PA position This chamber is contour-forming on the right and at this border is also frequently noted as having increased density. On the left contour the auricular appendage also projects sufficiently to cause a prominence of its own. Note the normal course of the barium-filled esophagus downwards, particularly at the aortic level.

metrical or asymmetrical, and from the proportionate degree of enlargement of each of the chambers, proper inferences may be drawn. Examples of asymmetrical generalized chamber enlargement are hypertensive or rheumatic valvular heart disease Examples of symmetrical generalized cardiac chamber enlargement are severe primary or secondary anemias, myxedema (here there may also be pericardial effusion), thiamine deficiency, amyloid and glycogen storage diseases, diffuse focal and interstitial myocarditis

largement, added to the previous outflow tract enlargement, is almost always indicative of current, impending, or past failure, and generally prognostic of a relatively early demise Marked enlargement of the right ventricle may occur rapidly with pulmonary embolism and infarction, evidence of right ventricular failure being added to the acute signs of pulmonary distress

RIGHT ATRIUM

This chamber, lying between the superior and inferior venae cavae, can be conveniently divided into two portions the smooth intervenous portion lying posteriorly, and the trabeculated portion lying anteriorly and lateral to it Enlargement of the chamber occurs early in the trabeculated portion and is most readily observed as the elongation of the appendicular portion in the slight rotation towards the RAO position More severe degrees of enlargement cause further elongation of this oblique or shelf-like contour Enlargement of the posterior portion of the atrium occurs relatively late in the course of enlargement of this chamber

Slight or Moderate Right Atrial Enlargement. These grades of enlargement are not uncommon in rheumatic heart disease, even in the absence of clinical manifestations of heart failure In pulmonary heart disease and in left ventricular failure, right atrial enlargement is almost invariably associated with current or past manifestations of right heart failure.

Marked Right Atrial Enlargement. More severe grades of enlargement are common in rheumatic heart disease, secondary to either right ventricular failure or organic involvement of the tricuspid valve. Somewhat lesser grades of enlargement may be found in congenital heart disease with left-to-right shunt, and tricuspid stenosis or atresia. The roentgenological distinction between enlargement of the trabeculated portion of the right atrium (including the right appendage) and the smooth portion between the orifices of the superior and the inferior venae cavae is not too important since really marked grades of right atrial enlargement may occur without involvement of the smooth posterior portion

GENERALIZED CARDIAC ENLARGEMENT

In the majority of cases of organic heart disease, more than one chamber is found to be enlarged (multiple chamber enlargement). Enlargement of all chambers may be termed "generalized chamber enlargement." When the enlargement of all the chambers is more or less symmetrical, a uniform or systemic agent is usually found to be responsible. Generalized chamber enlargement, therefore, may be sym-

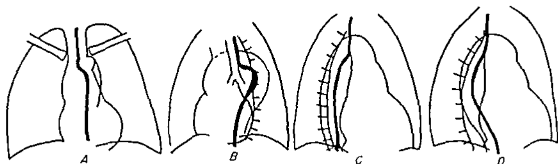


Fig. 3-38. A Adhesions between the aorta and the esophagus cause the displacement of the latter to the left just below the level of the aortic knob, when the aortic arch is elongated sufficiently to displace the descending aorta into the left costovertebral sulcus B Pulling of the barium-filled esophagus posteriorly in the LAO position When this occurs, as well as displacement to the left in the PA position, the use of the barium-filled esophagus to delineate left atrial enlargement may be erroneous. C RAO position· Illustrating the same principle as in (A) and (B) where pulling of the barium-filled esophagus causes posterior displacement of the esophagus which is not due to left atrial enlargement, even though the latter is present D Another example of pulling of the barium-filled esophagus by aortic adhesions here it is pulled backwards above, and displaced anteriorly below. Left atrial enlargement in such instances as these must be demonstrated prior to filling the esophagus with barium.

metrical or asymmetrical, and from the proportionate degree of enlargement of each of the chambers, proper inferences may be drawn Examples of asymmetrical generalized chamber enlargement are hypertensive or rheumatic valvular heart disease Examples of symmetrical generalized cardiac chamber enlargement are severe primary or secondary anemias, myxedema (here there may also be pericardial effusion), thiamine deficiency, amyloid and glycogen storage diseases, diffuse focal and interstitial myocarditis.



Auscultation and phonocardiography

Auscultation
CAMILLE LIAN

Use of Written Symbols to Describe Cardiovascular Sounds and Murmurs
HAROLD N. SEGALL

Technical Aspects of Phonocardiography
RUDOLF ZALTER AND ALDO A. LUISADA

Clinical Phonocardiography
ALDO A. LUISADA AND CHRIST ARAVANIS

AUSCULTATION

HISTORY

It has been known since the time of Hippocrates that application of the ear to the chest wall reveals respiratory and cardiac sounds. Certain ancient authors, like Coelius Aurelianus, knew about auscultation. Double (1817) advises one to "approach one ear to the chest wall." Corvisart's pupils, like Bayle and Laennec, followed this procedure in order to follow the heart beat more easily in cases where palpation of the pulse was difficult. Thus, cardiac auscultation remained for a long time a curiosity with no practical use. The "father" of auscultation is Laennec. His arduous work resulted in the publication of his "Treatise on Auscultation" (1819), an admirable clinical tome describing the normal heart sounds and the organic and inorganic heart murmurs.

THE TWO NORMAL HEART SOUNDS

Laennec described the heart sounds as follows: the *1st sound* is dull, somewhat long, and synchronous with the contraction of the heart and the arterial pulse, the *2d sound* is sharp, short, and synchronous with the beginning of diastole. This timing of the heart sounds in relationship to cardiac contraction was confirmed later by Turner, Marc d'Espine, and Hope (1830–1831).

Shortly afterwards (1832), Rouanet described the short pause between the 1st and 2d sounds. He also stated that the 1st sound is valvular in origin, due to the closure of the atrioventricular (AV) valves and to their subsequent distention (similar to the flapping of a sail spread to the wind); the 2d sound was explained as caused by the sudden closure of the semilunar valves. Rouanet further described the heart murmurs. a soft systolic murmur near the apex, in patients with incompetence of the mitral valve, a harsh systolic murmur at the base, in patients with stenosis of the arterial openings; a diastolic murmur at the apex, in stenosis of the mitral valve; and a diastolic murmur at the base, in insufficiency of the semilunar valves.

Two committees, in Dublin (1835) and London (1836) confirmed Rouanet's data. However, many erroneous concepts were subsequently advocated. Magendie (1835) attributed the two sounds to the impact of the heart against the chest wall, Piorry (1834) tried to demonstrate that the valvular

action does not produce sounds; Hope (1834) considered the possibility that the 1st heart sound was due to collision of the blood molecules and the 2d to a rebound of the ventricular walls hit by the blood flow from the atria, Burdach (1834) thought that the heart sounds were caused by the *flow of blood into a chamber containing air;* Beau (1840) believed that the 1st sound was synchronous with the end of ventricular diastole, that the apical impulse was due to the effects of the atrial contraction, and that the 2d sound was caused by dilatation of the atria hitting the chest wall

All these hesitations and contradictions were definitely abolished by the physiological studies of Chauveau, Faivre, and Marey (1857–1863), with their convincing tracings and deductions.

MURMURS OF THE HEART AND THE GREAT VESSELS

Laennec described the murmurs of the heart as "bruit de soufflet" because *they resemble the* noise made by a bellows. *He described:* (1) the "true souffle," which *is always diastolic;* (2) the harsh murmur (*"bruit de scie ou de rape"*); and (3) *the musical* murmur.

Bouillaud described three main categories *of murmurs:* (1) murmurs due to valvular lesions or abnormal shunts. *the organic murmurs,* (2) murmurs produced by *dilatation of* a valvular ring: *the functional murmurs,* (3) murmurs due to anemia. *the hemic murmurs.*

He attributed both organic and *functional* murmurs to the increased friction of the blood flowing through a narrowed passage and *correlated* the hemic murmurs with *a decreased* density of the blood These explanations were subsequently accepted by most clinicians. In patients without cardiac lesions, increased cardiac dynamics was accepted as a cause of murmurs

Corrigan's observations (1838) deserve mention. According to him, the conditions which determine the appearance of murmurs are the cause of eddy currents which may replace the normal flow and decrease the tension of the heart walls.

The most precise and conclusive studies were made by Chauveau He summarized the result of his experiments in the following way: "Every murmur results from the vibration of a stream of blood flowing from a smaller into a larger chamber, whether the dilatation is absolute or relative." All subsequent works, particularly those of Marey, confirmed Chauveau's conclusions It is important to remember that a significant difference between the caliber of the two chambers or vessels causes a difference in intravascular pressures and accelerates the blood flow. Alone, an increase in the speed of blood flow is not sufficient to produce a murmur, as was erroneously believed by Weber (1854) and Bondi (1936). Marey postulated that the murmurs are due to eddy currents produced in enlarged chambers. His theory was subsequently demonstrated by experimental studies of Heynsius.

THE HUMAN EAR AND ITS LIMITATIONS

The human tympanic membrane is sensitive to the motions of the air, i e, to variations in *its pressure,* if the vibrations have sufficient *frequency and* magnitude. The human ear perceives a sound if its amplitude is above the sensitivity threshold for that particular frequency. *Sensitivity threshold* can be defined as the lowest amplitude at which a sound can be perceived.

Fletcher's curves show that, the lower the frequency range, the higher must be the *magnitude* of a sound in order to be heard. Audibility increases on a logarithmic curve The lowest frequency of audibility is about 20 vibrations per second, where only sounds of great intensity can be heard. In the range of 800 vibrations per second, however, *even very* small sounds can be heard.

Sounds in general have three qualities: *pitch,* or frequency (number of vibrations per second); *amplitude* of these vibrations; and *timbre,* a *characteristic quality* of a sound which derives from the fact that components of different frequencies are simultaneously perceived

Noise is a sound caused by irregular vibrations or by the combination of a nonharmonious group of frequencies of very short duration The auscultatory phenomena of the heart and of the great vessels are *essentially* noises. While the timbre of these noises is easily perceived, vibrations of the same intensity are heard as louder sounds if they are in the higher frequency *range* Superimposition of

two inaudible vibrations of low frequency may be heard because of the resultant higher frequency.

Classification of Cardiac Auscultatory Phenomena. Among the cardiac vibrations, the human ear perceives those which are in the frequency range between 20 and 1,000 vibrations per second, and particularly those in the range of 30 to 800. These vibrations can be divided as follows. (1) heart sounds (including split sounds), (2) murmurs (blowing, rumbling, or musical); (3) friction rubs

Education and Training of the Ear: Routine Technique. Undoubtedly training and education of the ear are necessary for proper auscultation The 1st heart sound immediately precedes the pulse, the 2d follows it. Between the 1st and the 2d sounds there is a short pause After the 2d sound, there is a long pause which precedes the 1st sound of the following cycle. This pause is shorter in tachycardia

A systolic murmur is heard during the pulse of an artery, the diastolic murmur after the pulse. One should note whether or not there is a short interval between the 1st sound and a systolic murmur, if there is, the murmur is called *midsystolic* (mesosystolic) or *late-systolic* (telesystolic). The former occurs in mid-systole, the latter at the end of systole

It is difficult sometimes to "time" an additional sound, which causes a *triple rhythm.* Splitting of a heart sound is usually recognized because the time interval between its two components is very short. The maximum intensity of the 1st sound is along a line from the xiphoid to the apex, that of the 2d sound, at the base of the heart

A procedure useful in recognizing the localization of certain murmurs or of extra sounds is first to find an area where only the normal heart sounds are audible, and then proceed toward the area of maximum intensity of the 3d sound: there will be a transitional zone where timing of the additional sound is possible.

The characteristics of the heart murmurs are. phase, point of maximum intensity, and transmission within the precordium or to the axilla, the back, and along the great vessels In addition, one should describe the apparent clinical loudness of the murmur.[1]

It is best to start auscultation in the 1st *right* intercostal space and follow the sternal border down to the 6th. In that area, triple rhythms are rare and murmurs less frequent than along the left sternal border. It is easy to recognize the heart sounds and to time murmurs in relation to the sounds. The same procedure should be repeated along the *left* sternal border. Then, one proceeds to the auscultation of the apex and from there towards the left axilla. It is important to place the patient in *lateral decubitus* when listening to the apex. Cardiac auscultation has to be repeated with the patient in *sitting* and *standing* positions. Occasionally, it will be necessary to listen again after having submitted the patient to *exercise tests.*

Education and training of the ear can be facilitated today by collective audiovisual demonstrations which save time and spare errors.

STETHOSCOPES

The first stethoscope was invented by Laënnec. His instrument was a wooden tube, 30 cm long and 3 cm in diameter, which he covered at the lower end with a membrane. Laënnec's stethoscope was modified by Piorry, who flattened the ear end and widened the chest end like a bell Later, binaural stethoscopes with rubber tubing were introduced (Cammann, 1851).

The significance of the *chest piece* of the stethoscope should be emphasized. A stethoscope ending in a flat chamber closed by a membrane is very effective if it is applied to the chest in lateral decubitus. While an open bell transmits low-pitched sounds and murmurs better, membranes are more useful in listening to high-pitched murmurs (Routier, Cossio, Rappaport and Sprague) Therefore, it is useful to use a stethoscope with interchangeable chest pieces

Electrically amplified stethoscopes present few advantages, except for doctors with hearing defects

NORMAL HEART SOUNDS

The First Sound. The 1st heart sound occurs at the beginning of ventricular systole, it is somewhat dull and of deep tonality, its point

[1] The loudness of heart murmurs heard clinically has been graded by S. A Levine on a scale from 1 to 6 This is so well known that it does not need description. *Editor.*

of maximum intensity is usually at the apex or at the 4th or 5th intercostal space It is usually longer than the 2d sound. It is principally due to the closure of the AV valves, either in itself or because of their vibration Marey states that a sudden contraction of the myocardium and a sudden arrest due to the closure of the valve produce the 1st sound. This definition may still be nearer to the truth than many subsequent ones

Study of the splitting of the arterial sounds led the author to the belief that *the vibrations of the aortic and pulmonic valves contribute to the genesis of the 1st sound* On the other hand, a study of the 4th heart sound inclines him to the belief that vibrations of the atrial walls *do not* contribute to it

The Second Sound. The 2d sound is clearer, sharper, and shorter than the 1st. Its area of maximum intensity is at the 2d or 3d intercostal space at the left of the sternum It is generally accepted that this sound is due to the closure of the semilunar valves

The Third Sound. It was described by Einthoven, Gibson, Hirschfelder, and Thayer (1907–1910). Since then, it has been the object of several studies. It can be heard best between the xiphoid and the apex The 3d sound occurs after the 2d, with a certain interval between them. The pause between the 2d and the 3d sounds is longer than that between the two components of a split 2d sound Various authors agree that the 3d sound can be heard best when the patient is in lateral decubitus and often disappears when he stands up Tachycardia renders the 3d sound louder. Therefore, it may be heard immediately after the patient lies down although it may disappear after rest The mechanism of the 3d sound is still under discussion The general opinion is that it is due to distention of the myocardium during the phase of *rapid diastolic filling* However, the author also admits valvular vibrations as secondary components The 3d sound is more common in children and young adults It can be heard in 15 to 20 per cent of patients up to the age of 10, in 50 per cent between 10 and 20, in 15 to 20 per cent between 20 and 30, in 8 per cent between 30 and 40, and in 1 per cent between 40 and 50 (Thayer) Except for a few dissenting observers, the 3d sound is considered a physiological phenomenon.

The Fourth Sound. This sound appears only exceptionally. The author admits that it is due to splitting of the 1st heart sound.[2]

SPLITTING OF THE FIRST HEART SOUND

This may occur in both physiological and pathological conditions. The two components are very near to each other, without a definite silent interval between them Frequently, the second portion is louder and of higher tonality than the first. The point of maximum intensity is at the apex or in the 5th intercostal space at the left of the sternum Potain pointed out that it can be heard best at the end of expiration and at the beginning of inspiration. It may be constant and heard best when the patient is standing It might be due to asynchronism between the contraction of the right and left ventricles. Orias and Braun-Menendez believe that the central phase of the 1st sound contains two parts, one coinciding with the isometric contraction, the other with the beginning of ejection. According to them, there might be a separation of the two parts, causing an audible splitting With the exception of cases of bundle branch block or ventricular premature beats (where the splitting may be the result of ventricular asynchronism), the author believes that its presence indicates forceful cardiac action, like that of patients with *left* ventricular hypertrophy due to hypertension or aortic valvular defects. In such cases, it may be the result of the contraction of an abnormally strong left ventricle

Splitting of the First Sound Due to the Fourth Sound Certain phonocardiograms reveal presystolic vibration of low frequency (Wiggers and Dean, Orias and Braun-Menendez) However, Lian and Minot and Rappaport and Sprague, using systems which eliminate low-pitched vibrations (logarithmic microphones, corresponding to sounds audible to the human ear), do not record these vibrations In cases where a splitting of the 1st sound was audible, the author has always found a separation between the two large vibrations Among 50 healthy students, only one had an audible presystolic sound which could

[2] It is generally accepted that the 4th sound is intimately connected with the atrial contraction *Editor.*

be recorded in the phonocardiogram (Lian and Hubert). In cases of prolongation of the atrioventricular conduction, a presystolic sound due to the atrial contraction can be heard and recorded. Gallavardin calls this "galop du bloc." In exceptional cases, an atrial contraction causes one sound with two groups of vibrations The first of them coincides with the end of P, the second occurs slightly later. While the first is explained as a fourth sound, the second can be accounted for by valvular vibrations (Lewis, Lian).

Splitting of the First Sound due to Arterial Factors. This has been described by Potain and later by Wolferth and Margolies, and called "systolic gallop" In studies done with Welti, the author observed that this type of splitting was more frequent at the pulmonic area in patients with an x-ray finding of a dilated pulmonary artery. Phonocardiograms revealed either a second large vibration or an increase of the last phase of the 1st sound. This sign may be useful in the diagnosis of diseases of the pulmonary artery, including cases of pulmonary hypertension, as it can be subsequently confirmed by cardiac catheterization. *A similar phenomenon can be found over the aortic area if the aorta is dilated*

The auscultatory characteristics of the *protosystolic pulmonic snap* are. (1) that it is always louder during expiration, and (2) that the first part of the 1st sound is so weak that only the snapping second part can be heard, thus, one has the impression that there is a snapping 1st sound at the pulmonic area This pulmonic snap is present in patients with congenital heart disease and in those with acquired cardiac and pulmonary diseases associated with pulmonary hypertension

The exact mechanism of the protosystolic snaps, aortic or pulmonic, has not been established yet. It is not known whether the snap is produced by sudden tension of the semilunar valves, vibrations of the arterial wall, or some other factor.

These snaps should not be called gallop sounds but *protosystolic (aortic or pulmonic) snaps.* They cause an actual splitting of the first sound (*arterial splitting of the first sound*)

SPLITTING OF THE SECOND SOUND

Splitting of the 2d sound in the 2d or 3d intercostal space at the left of the sternum is a common finding in healthy individuals. This *physiological splitting* is usually heard at the end of inspiration or at the beginning of expiration (Potain). Sometimes, however, it is constant. This splitting is due to changes of the intraventricular pressures brought about by inspiration and resulting in an asynchronism of closure of the semilunar valves of the aorta and pulmonary artery. Splitting of the 2d pulmonic sound is usually due to a delay of closure of the pulmonic valve. The first component corresponds to closure of the aortic valve; the second, to closure of the pulmonary valve (Leatham).

Pathological splitting of the 2d sound is usually permanent, but may be intermittent because it is still influenced by respiratory variations. *Splitting of the second pulmonic sound* is present in all conditions which increase either the pressure or the flow of the pulmonary artery, e g., atrial septal defects, moderate pulmonic stenosis (Leatham observed that it is clinically absent in severe stenosis), primary pulmonary hypertension, secondary pulmonary hypertension, congestion of mitral stenosis, and the secondary pulmonary hypertension of cor pulmonale. It can be found in right bundle branch block and in left ventricular extrasystoles. In both, right ventricular contraction follows the left

Splitting of the 2d aortic sound can be found in systemic hypertension and in moderate aortic stenosis (so-called *paradoxical splitting* —Leatham). It can be observed in left bundle branch block and in right ventricular extrasystoles. In both, left ventricular contraction follows the right.

Splitting of the 2d sound should be distinguished from the opening snap of the mitral valve, the 3d heart sound, the pericardial snaps, and the early-diastolic gallop The interval between the two elements of a split 2d sound can be short or wide In bundle branch block, the author and coworkers noticed that the width of the splitting is proportional to the duration of the intrinsicoid deflection

MODIFICATIONS OF LOUDNESS OF THE HEART SOUNDS

Decreased loudness of both sounds occurs in myocardial diseases causing a weakening of the contraction, in pericardial effusions, and in pulmonary emphysema, in which the distance

between the heart and the chest wall is increased Decreased loudness of *one* of the heart sounds may be due to valvular lesions

Increased loudness of both heart sounds occurs in myocardial hypertrophy, in certain tachycardias, and in the presence of pulmonary consolidation which increases the transmission of the sounds Increased loudness of *one* of the two heart sounds can be found in certain diseases: loud 1st apical sound and 2d pulmonic sound, in mitral stenosis; loud 2d aortic sound, in hypertension or aortitis The loudness of the sound can be so great that it can be perceived through the chest by palpation

TRIPLE RHYTHMS

A triple rhythm is caused by the addition of an extra sound to the two normal heart sounds (Evans). Additional sounds can be found in diseases of the endocardium, myocardium, or pericardium

This rhythm was described by Potain (1875), who called it *gallop rhythm* He distinguished between *presystolic* and *protodiastolic* gallop. He believed that the former was due to distention of the ventricular wall caused by the atrial contraction and the latter to rapid, passive filling of the ventricles at the beginning of diastole. Later, Wolferth and Margolies (1933) described the *summation type of triple rhythm*, which occurs most often *in tachycardia* Because of the short diastole, the atrial contraction occurs at the time of rapid filling, i e, at the beginning of diastole. *Then, the* distention of the myocardium is due to two simultaneous factors, i e., atrial contraction and rapid passive filling Potain also distinguished *right* and *left ventricular* types.

Classification of Triple Rhythms. These can be divided into three groups, as follows.

I The 2d sound is isolated while the other two sounds are close to each other
  A Between the xiphoid and the apex
    1. Splitting of the 1st sound
    2. Presystolic type (gallop) *
    3 Fourth heart sound
  B At the base
    1. Arterial splitting of the 1st sound due to the early-systolic snap of the aorta or of the pulmonary artery

II. The 1st sound is isolated, while the other two sounds are close to each other
  A At the base
    1. Splitting of the 2d sound
  B Between the xiphoid and the apex
    1. Third heart sound
    2. Early-diastolic type (gallop) †
    3. Late-systolic pleuropericardial snap
    4. Pericardial vibration (in pericarditis with calcification)

III Other cases
  A. Mesosystolic metallic snap (in hydropneumopericarditis)
  B. Short mesosystolic cardiopulmonary murmurs, giving the impression of a sound or snap
  C. Mesosystolic pericardial snap (in constrictive pericarditis)

Left Ventricular Presystolic Type. The left ventricular presystolic type is usually due to a somewhat dull sound which precedes the 1st sound, the point of maximum intensity is at the apex or at the left of the xiphoid The 1st sound is usually of poor intensity but it may be normal. The heart rate is *usually rapid*, but may be normal or even slow. In lateral decubitus, this rhythm is *loudest at the apex.* It is generally constant, but *may vary with* breathing, or be present only *briefly after the* patient lies down. Usually, *it is easy to* distinguish between a presystolic triple rhythm and a split 1st sound, because between *the two* split components of the 1st sound there is no silent interval, while the presystolic sound is separated from the 1st sound by *an appreciable* pause. However, in certain *types of* bundle branch block, the splitting *of the 1st* sound can be wide. In patients with a short *P-R interval*, there may be a *delayed presystolic gallop* (Lian and Welti). The presystolic extra sound usually occurs at the end of the P wave, while the 1st heart sound is at the peak *of the* R wave or from 0 02 to 0 03 sec after the peak of the R wave If the R starts immediately *at the end of* the P wave, the extra sound and the 1st sound may be juxtaposed, without interval. Therefore, *in doubtful* cases, a phonocardiogram should be taken: *if* both vibrations are after the peak of the R wave, *it is* a split 1st sound, but if one is before and the *other* after the peak of the R wave, it is a triple rhythm

* According to modern views, this type of triple rhythm is caused by increased loudness of the 4th sound. *Editor.*

† According to modern views, this type of triple rhythm is caused by increased loudness of the 3d sound. *Editor.*

Left Ventricular Protodiastolic Type. This has the same characteristics as the presystolic, with the difference that the extra sound occurs after the 2d sound. It should be differentiated from the following diastolic extra sounds:

1. *Splitting of the 2d sound:* the two components are closer and the point of maximum intensity is at the base.

2. *Physiological 3d heart sound:* in the author's opinion, this is an intermittent finding.

3 *Opening snap of the mitral valve:* the snap is shorter and has a maximum intensity in the 4th or 5th intercostal space. Usually, in the presence of an opening snap or diastolic rumble, other auscultatory signs of mitral stenosis are also present

Sometimes, on auscultation, four sounds can be heard due to the presence of *both* a presystolic and a protodiastolic extra sound This, however, is a rare finding, even in the presence of phonocardiographic evidence that there are four sounds, in such cases, the clinician usually hears only a triple rhythm

Lian has reported the coexistence of a presystolic gallop and a split 1st sound This can be diagnosed clinically, because the splitting is heard best with the patient standing while the triple rhythm can be heard best in the supine decubitus.

Diagnostic Value and Mechanism of Gallop. It is a common belief that the left ventricular triple rhythm is a sign of left ventricular failure (Merklen and Lian). Weakness of the myocardium may be initial or advanced In the first instance, the prognosis is far better The mechanism of the triple rhythm is still under discussion Potain believed that it was due to hypotonicity of the myocardium The author believes that it is connected with left ventricular failure and an increase of residual blood at the end of ventricular contraction The extra sound is produced by vibrations of the myocardium but a valvular component may contribute to it. Dock and his associates tried to prove that the origin of the sound is valvular.

Left or Right Types of Triple Rhythm. The right type of triple rhythm can be heard best at the epigastrium or in the 5th intercostal space at the left of the sternum. The left type is heard best at the apex. They are due to abnormal function of the right or left ventricle, respectively.

Whether they are due to left or to right ventricular failure can be determined only after complete physical examination, x-ray, and an electrocardiographic study.

MURMURS

The murmurs can be distinguished from the sounds because they are of longer duration and have a higher frequency. Most murmurs are *intracardiac* in their origin. The majority of them are *organic murmurs,* due to valvular lesions or congenital shunts. Certain murmurs are *functional,* due to incomplete closure of an intact valve because of dilatation of the valvular ring or other functional abnormality.

Besides these two varieties, one should mention a third type of murmur, the so-called "hyperergic murmurs," which are due to increased force or rapidity of the ventricular contractions. This mechanism has been invoked in order to explain the origin of the systolic murmur *in aortic insufficiency* or in atrial septal defects (Lian and Broustet).

Extracardiac murmurs were first described by Potain as "cardiopulmonary murmurs." Volume changes of the heart during systole may cause a sudden displacement of air in the overlying lung tissues. This originates vibrations which may give the auscultatory impression of a murmur. These murmurs are usually systolic, only exceptionally diastolic.

Murmurs can be *systolic* or *diastolic,* or *continuous through the entire cycle.* Besides the systolic and diastolic, there are two types of murmurs which unfortunately are sometimes confused One is the coexistence of a systolic *and* a diastolic murmur. The other is *the continuous murmur* The continuous murmur is caused by a continuous flow *in the same direction,* while a double murmur is caused by flows *in opposite directions*

Murmurs may be of different loudness. The organic murmurs are the loudest, they can be *musical, harsh, rasping,* or *soft.* Functional murmurs are usually *soft* but occasionally can be loud and harsh

Continuous murmurs are caused by continuous flow of blood from an artery into a vein or from an artery or cardiac chamber into another cardiac chamber with lower pressure Infrequently, a continuous murmur may be due to compression of a vein, even less frequently to compression of an artery. A continuous mur-

mur can usually be distinguished from a double murmur by auscultation, owing to the fact that it is louder in late systole and early diastole while the 2d sound is inaudible. In the double murmur of aortic stenosis and insufficiency, the systolic murmur ends before the 2d sound, and there is a short pause between the 2d sound and the diastolic murmur.

Transmission of Murmurs. Murmurs are usually propagated in the direction of the blood flow during the phase in which they occur, less frequently in the opposite direction The murmur due to *narrowing of the aortic valve* is most clearly audible in the 1st intercostal space at the right of the sternum, it is transmitted well to the supraclavicular notch and along the carotid arteries It is also propagated downward along the sternal border and to the apex The loudness decreases while the stethoscope is being moved from the focus of maximum intensity There are two additional factors which determine the degree of transmission, the type of tissue through which the murmur is transmitted to the ear, and the distance between the heart and the chest wall

Area of Maximum Intensity. According to older authors

[illegible] originates The author believes that this concept should be modified because the linear projection as well as the distance and the transmitting media influence the area where a particular murmur can be heard best.

Murmurs arising *at the tricuspid and pulmonic valves* can be heard most clearly at the areas of their projection on the chest wall because of their proximity with the latter On the other hand, murmurs *arising at the aortic valve* are loudest in the 2d intercostal space at the right of the sternum because the ascending aorta is nearer to the chest wall than the aortic valve The same interpretation explains the fact that murmurs arising *at the mitral valve* are loudest at or within the apex Experiments of Sautelle and Gret confirm these clinical observations

Types of Murmurs. General concepts in regard to cardiac murmurs have already been discussed Detailed descriptions of the murmurs of the various acquired valvular lesions and congenital defects will be presented in subsequent chapters

Hemic Murmurs. Severe anemia may cause ventricular failure and the onset of a systolic murmur due to functional incompetence of the mitral or tricuspid valve. There may also be tachycardia and a triple rhythm. However, there can be a systolic murmur without cardiac failure, in which case it may be due to overactivity of the heart: "hyperergic murmur" (Lian) or "cardiopulmonary murmur" (Potain).

AUSCULTATORY FINDINGS IN PERICARDITIS

Friction Rubs. Friction rubs can be midsystolic, early-diastolic and presystolic They may all be present in a given patient and give the auscultatory impression of a *locomotive murmur*. In the phonocardiogram, it is usually the presystolic murmur which is the most significant.

Pericardial Snaps. These appear in cases of chronic pericarditis. There are two main types, the *pleuropericardial* and *pericardial* The pleuropericardial snap was first described by Gallavardin and later studied by Lian. It usually occurs in midsystole or late systole. Sometimes it can be followed by a *late-systolic murmur*, which is a cardiopulmonary murmur due to sudden displacement of a portion of the lung

The pericardial snap, which may appear in cases of constrictive pericarditis, mostly in the presence of calcification, is loud and audible over the entire precordium (pericardial vibration of Lian) It usually appears in early diastole and may be due to a sudden vibration of the calcified tissues during early-diastolic filling (Cossio). In cases of constrictive pericarditis without calcification, the snap is not loud Another, smaller snap may occur in systole (Froment).

Pericardial snaps of *metallic* character occur when the pericardial sac contains liquid and air Tillaux describes the "water-wheel murmur" (*bruit de moulin*), which appears when both liquid and air are present between the chest wall, the pleura, and the pericardium

VASCULAR SOUNDS AND MURMURS

Arterial Sounds and Murmurs. The cardiac sounds are transmitted well to the proximal arteries of the neck while only one sound is audible in the peripheral arteries Compression of an artery evokes the appearance of a

systolic murmur; therefore, in evaluating the transmission of intracardiac murmurs, great care must be taken in placing the chest piece of the stethoscope.

In *coarctation of the aorta,* it is common to hear *a systolic murmur along the spine.* This murmur is louder than that heard over the 2d left interspace. It arises at the point of coarctation, is transmitted downwards and sometimes upwards. Often, one can hear a systolic murmur and feel a pulsation in various intercostal spaces, particularly if the patient bends forwards. This murmur is caused by the rapid flow of the dilated intercostal arteries.

Auscultation of *peripheral aneurysms* may reveal (1) a sound of distention; (2) a systolic murmur, (3) (occasionally) a diastolic murmur. The latter is typical of aneurysms of the ascending aorta and the diastolic murmur is probably caused by the coexisting aortic insufficiency. However, one should not completely exclude the possibility of a diastolic murmur due to the rebound of a large aneurysmal sac. It should be kept in mind that compression of an artery usually produces only a systolic murmur.

The *double murmur of Duroziez* in aortic insufficiency can be heard over the femoral artery by exerting increasing pressure with the stethoscope. When the endpiece of the stethoscope is placed lightly over the vessel, a loud sound can be heard, due to the sudden extension of the artery *(pistol-shot sound).* When the pressure is increased slowly, first a *systolic murmur* appears and then a *diastolic murmur.* Then, with more compression, the diastolic murmur disappears and, finally, the systolic murmur also disappears.

The *double sound of Traube* is infrequently heard. It appears in certain patients with aortic disease when pressure is lightly applied on the femoral or brachial artery. Dagnini and Pezzi believed that the second component of Traube's double sound was a presystolic venous sound transmitted to the femoral artery. However, this explanation does not apply to the sounds heard over the brachial artery.

Venous Sounds and Murmurs. As over the proximal arteries, cardiac sounds can be heard over the proximal (neck) veins, particularly over the jugular veins. Josué suggested auscultation of the neck veins in cases of AV block. He thought that the atrial contractions would become audible through the sounds corresponding to the A waves of the veins. The author believes that, in such cases, the apex is a better area of auscultation.

Continuous venous murmurs or *hums* are frequently heard in subjects with anemia, and occasionally in those without any disease, particularly children. They may be present in aortic insufficiency.

In hyperthyroidism, a *continuous murmur* over the thyroid gland is a characteristic sign, particularly when there is no basal systolic murmur over the heart, or if the thyroid murmur is louder than the cardiac systolic murmur. This thyroid murmur is chiefly audible over the superior vascular peduncle.

AUSCULTATION OF THE HEART AND OF THE GREAT VESSELS AT THE SUPRASTERNAL NOTCH

This type of auscultation should be performed *with the chest piece of the stethoscope* directed downwards, as if forcing it behind the sternum, and in forced expiration. This area is useful in the study of the transmission of certain aortic murmurs and also in making the differential diagnosis between a split 2d sound and an opening snap of the mitral valve.

CARDIOESOPHAGEAL AUSCULTATION

First reported by Hoffmann and Richardson (1892) *in a few case histories,* it was applied by Taquini and Braun-Menendez (1936) to phonocardiographic studies of the atrial sounds in normal individuals.

Lian made a systematic study in 25 subjects using an Einhorn tube introduced into the esophagus. This tube can be swallowed without difficulty and without local anesthesia. To its free end is connected a stethoscope. It is advisable to let the patient inhale deeply and then to let him exhale deeply before listening. If the tube is obstructed by mucus, 20 ml of air can be injected rapidly through a syringe. This method is particularly useful in the interpretation of certain systolic *murmurs* audible on the anterior chest wall. All valvular murmurs can be heard well by this method, and the one most clearly audible is the murmur of mitral insufficiency, its maximum intensity being at 30 to 40 cm from the dental arch. If there is a systolic murmur on the anterior chest wall, which is not audible through the esophagus, the diagnosis of mitral insufficiency should be dis-

carded On the other hand, if the murmur is only audible through the esophagus, this is sufficient for the diagnosis of mitral regurgitation

DORSAL PROPAGATION OF ANTERIOR CHEST WALL MURMURS

There are two ways by which a *mitral murmur* can be transmitted to the back: (1) through the enlarged left ventricle (the murmur is audible over the entire left lower lobe), (2) through the left atrium (the murmur is audible over the lower scapular angle). *Aortic systolic murmurs* are transmitted to the right upper part of the back; *pulmonic systolic murmurs* are transmitted to the upper part of the left scapula. The *high-pitched, musical, cardiopulmonary, telesystolic murmurs* are also transmitted to the back, as well as certain *continuous murmurs*. Exceptionally, *pericardial friction rubs* can be transmitted to the back either because they are very loud or because they are due to a posterior pericarditis.

USE OF WRITTEN SYMBOLS TO DESCRIBE CARDIOVASCULAR SOUNDS AND MURMURS

Laennec used symbols when he tried to describe the jugular venous hum with musical notation At least since the time of Gairdner (1862) linear rectangles for sounds and vertical lines for murmurs have been used to illustrate temporal relationships, but these symbols are only casually quantitative and ignore relative loudness and quality. In 1926 it occurred to the author that, by giving the lines certain values, the symbols could be written quantitatively to describe relative loudness, duration, and dominant quality of sounds and murmurs This would call for training the ear and the hand to measure these attributes and depict them with appropriate symbols. In the course of about 20 years this method evolved into its present form (Fig 3-39).

The rules of the method are shown in the left upper section Loudness is represented by vertical, and duration by horizontal lines in drawing a rectangle to depict a sound Low-pitched, rumbling, or coarse murmurs are described by widely spaced waves of lines and high-pitched, blowing, or whiffy murmurs, by closely packed vertical lines The loudness of the murmur is reflected in the height of the lines and its duration in the space the symbol occupies along the abscissa To note special qualities such as ringing, musical, amphoric, or creaking, the word is written near the symbol. The symbol for a friction murmur is written above the base line to indicate its superficial quality.

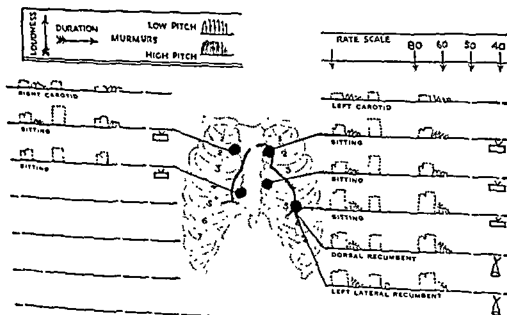


Fig 3-39. Chart for recording cardiovascular sounds and murmurs.

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The rules of the method are shown in the left upper section. Loudness is represented by vertical, and duration by horizontal lines in drawing a rectangle to depict a sound. Low-pitched, rumbling, or coarse murmurs are described by widely spaced waves of lines and high-pitched, blowing, or whiffy murmurs, by closely packed vertical lines The loudness of the murmur is reflected in the height of the lines and its duration in the space the symbol occupies along the abscissa To note special qualities such as ringing, musical, amphoric, or creaking, the word is written near the symbol The symbol for a friction murmur is written above the base line to indicate its superficial quality.

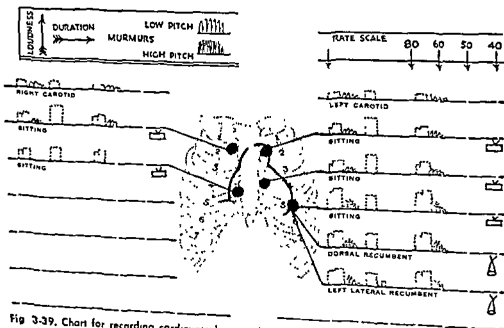


Fig 3-39. Chart for recording cardiovascular sounds and murmurs

The diagram of the thorax and the silhouette of the heart afford a simple way of indicating where the chest piece of the stethoscope is held by marking dots from which lines are drawn; on these the symbols are written Under the end of each line there is a symbol for the type of chest piece used In this specially devised chart, the pattern of standard normal heart sounds with physiological systolic murmurs (derived from a statistical study of 200 selected normal subjects) provides guidance in writing the symbols for auscultatory signs in a given patient. The symbols are written over the faintly printed "normals."

In the left lower section at the bottom of the chart there are lines on which symbols for sounds and murmurs heard at other points over the chest may be written, above the diagram of the thorax, there are lines for symbols to depict what is heard over the carotid arteries In the right upper section there is a scale for guidance in showing the heart rate by placing the 1st sound at the end of the diastolic period. The pattern of faintly printed symbols shows a heart rate of 80 In the epigastric region, it is convenient to record the blood pressure.

Charts of this kind, 4 by 6 in , in books of 50 pages, are available, on these pages all the printing is as faint as the symbols of the heart-sound pattern in this figure This permits the use of these pages for ordinary written notes as well as for the symbols.

Given good motivation, namely, desire to learn about auscultation, skill in using this method can be readily achieved by anyone with an ordinary sense of hearing No special musical or other auscultatory talent is required Having in mind the dynamics of the cardiac cycle in order to "time" correctly, each unit of sound is examined and its attributes measured by focusing the sense of hearing on it. While one hand holds the stethoscope, the other writes the symbols Thus, as the pattern of sounds and murmurs is analyzed by the sense of hearing, it is synthesized by the symbols.

The use of both this method and the phonocardiogram in a given case provides more accurate information than one method alone The electrical instrument records temporal relationships and also low-pitched, low-amplitude vibrations better, the human ear and hand record high-pitched, blowing murmurs better. The two methods are about equal in efficiency for recording relative loudness The human ear is obviously superior in distinguishing between the thud-like quality of a sound and the peculiar noise which is a murmur

A pen nib, fine enough to write the symbol for a faint, high-pitched, whiffy murmur, should be used. The book of heart-sound charts, or other paper on which the symbols are to be written, should be placed on the bed or table to make writing while listening readily feasible

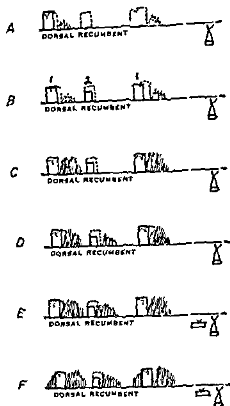
Figure 3-40A illustrates the analysis and synthesis of the pattern of heart sounds and murmurs heard at the apex of the patient whose complete chart is shown in Fig 3-40B. As each unit of the pattern is heard and its characteristics are seized by the sense of hearing, the symbol is written

The 1st sound is identified quite easily, for purposes of timing, because the heart rate is 80 Moreover, at the first "glance" with the sense of hearing, the systolic and diastolic murmurs become apparent. Having completed the task of timing, the attributes of the 1st sound are measured and the result recorded (*A*). Next, the 2d sound is treated similarly and the symbol for the 1st sound of the next beat is written to delimit one complete cardiac cycle showing the relative duration of the systolic and diastolic intervals (*B*). Then, the most obvious, loudest, and longest murmur is measured and its symbol written (*C*). A search is made for a 3d sound or opening snap of the mitral valve None can be heard. The decrescendo phase of mitral diastolic murmur is measured and recorded (*D*). By focusing on the phase immediately after the 2d sound, to check the duration of the expected period of quiet, it is found to be occupied by a faint whiff, the semilunar valve murmur transmitted to the apex (*E*). Then the duration of the interval of quiet between the end of the decrescendo and the beginning of the crescendo phase is measured before writing the symbol for the crescendo presystolic murmur, the loudness of which is measured in terms of the loudness of the 1st sound which interrupts it (*F*). The trained ear and hand require about 5 to 10 sec for each of the six steps

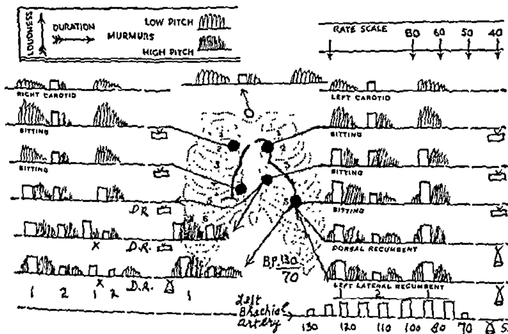
Figure 3-40B illustrates the heart sounds and murmurs in a case of rheumatic aortic and mitral stenosis and insufficiency. The heart sounds and murmurs in this case may be described in one of the three following ways

1. Briefest descriptive note (15 words). Mitral and aortic systolic and diastolic murmurs; stenosis and insufficiency of both valves, occasional extrasystoles

2 Less brief descriptive note (100 words): Coarse, loud (grade 3) systolic murmur of aortic stenosis, loudest at aortic area, heard over the carotid arteries Blowing diastolic murmur of aortic insufficiency heard all over the precordium, loudest at the left border of the sternum near the 4th intercostal space (grade 3) Decrescendo-crescendo murmur of mitral stenosis loudest at apex in the left lateral recumbent position (grade 2). Blowing systolic murmur (grade 3) follows sharp 1st sound at apex where 2d sound is faint, accompanied and followed by the blowing diastolic murmur of aortic



A



B

Fig. 3-40. A. Analysis and synthesis of pattern of heart sounds and murmurs heard at apex of heart B Complete chart of patient in (A) (From Segall, Am Heart J 8 533, 1933.)

insufficiency; and this is followed by the decrescendo murmur of mitral stenosis. Occasional premature beats, some with a loud 1st sound.

3 A complete description, equivalent to the record made with the symbols, was written in 629 words. An example of one part of this long clinical note is the following: "Over the carotid regions and in the suprasternal notch, the 1st sound is masked by a low-pitched, coarse systolic murmur, *the 2d sound is faint and followed by* a short blowing diastolic murmur The systolic murmur is louder over the suprasternal notch (where it has about the amplitude of a normal 2d sound at the apex) than over the carotid regions where it is about as loud as the 2d sound in this area."

The briefest note in words labels the case; it leaves to the imagination the precise nature of the auscultatory signs. The less brief description provides some information about the loudness and quality or pitch of the murmurs and their sites of maximum intensity, thus giving some of the substance from which the diagnostic label is derived *Neither effort seeks to describe precisely all the* details which the listener does or can detect. The symbols do make this possible The long, verbose description of the abundant details seized and held in the graph proves that it would be impractical to use words to describe such auscultatory signs in each case, even if it were possible to remember all these details long enough to write or dictate the notes. The graph can be read at a slow glance, whereas the wordy description would be tedious to read. "One picture is worth a thousand words."

The quantitative symbols prove their usefulness above all in training the student of cardiovascular sounds and murmurs in the art and science of clinical auscultation. By practicing this method daily, the ability to estimate relative loudness, duration, and pitch is acquired, and accuracy is sharpened. When writing the symbols, the observer is acutely aware of the fact that they will serve for comparison with other observations made in the past or to be made at a future date on the given subject. This encourages him to devote the necessary time and patience to achieve as great a degree of accuracy as possible in order to make the record a dependable one. Because writing the symbols while listening eliminates the insecurity of memory and clumsiness of writing a long description, the observer can afford the time to listen long enough to detect and measure all the signs and record them with maximum precision.

TECHNICAL ASPECTS OF PHONOCARDIOGRAPHY

The evolution of phonocardiographic technique has been beset since its inception by a multiplicity of factors pertaining to the nature, perception, and registration of sound It is perhaps not well understood that the spectrum of vibrations generated by the heart beat and transmitted through the tissues to the body surface constitutes a single entity and one physical phenomenon *This vibrational spectrum, extending over a band of approximately 1,000 cycles (1 to 1,000 cps), overlaps only partly the area of auditory perception* The subdivision of the vibratory spectrum into audible, partly audible, and subaudible bands, is therefore necessarily imposed by the physiological limitation of auditory perception and not through any physical difference in the phenomena under consideration Moreover, an element of linear distortion is naturally introduced by the ear in auditory perception, so that correct analysis and evaluation of the audible part of the vibratory spectrum is impossible through auscultation alone.

A *transducer* is theoretically capable of *linear* translation into electrical equivalents of all the vibrations transmitted to the chest wall without modification of intensity. Such a system of recording, though ideally suited for the study of all vibratory phenomena, is impractical because the intensity of the vibrations within the spectrum is an inverse function of their frequency. *For this reason, in a system of linear recording, the low-frequency vibrations have such a magnitude that they dominate the picture, while the high-frequency components can hardly be seen, being smaller and much less intense* Further magnification of the total phenomenon is of course precluded by the physical limitations of the paper (its width) Any attempt to eliminate the linear distortion introduced by the ear through the introduction of a linear transducer has, therefore, proved impossible

Early in the course of the development of phonocardiography, it became evident that no *single unified system of recording could* be adopted that could satisfy the various conflicting requirements which are necessary for the

registration of the *total vibratory* spectrum. It is obvious that a certain measure of linear distortion (attenuation) of the low-frequency, high-intensity vibrations has to be introduced if a record of the *total phenomenon* is desired. The resulting phonocardiogram is at best a compromise, necessitated by the intensity distribution of the various vibrations. It is in the extent and degree of this compromise that phonocardiographic apparatus differ from each other. Accurate standardization of the phonocardiogram has been hampered and delayed by this technical disparity.

PHYSICAL PRINCIPLES OF VIBRATIONAL PHENOMENA

Principles of Acoustics. The word *sound* is used to cover both a series of vibrational motions and the resulting phenomenon of auditory perception. The range of the vibrational phenomena covered by the word "sound" extends, however, beyond the band of physiological perception, which is limited in frequency and magnitude. The principles of acoustics apply, therefore, to the total phenomena of vibratory energy, irrespective of whether they lie in the auditory range.

Generation of Sound. Sound is generated by any vibrating body, solid, liquid, or gaseous. The motion performed by a vibrating body approximates in its simplest form the ideal of *simple harmonic motion*. In its most complex form, it can be analyzed and reduced to a number of simple harmonic components (Fig 3-41E). "Simple harmonic motion" may be defined as a *linear oscillating motion*, in which the *restoring* force is always proportional to the magnitude of the displacement, but is opposite to it in direction. The details of simple harmonic motion are best illustrated by the projection of a circular movement upon the diameter of a circle (Fig 3-41A). In order to locate the position of an oscillating particle, of mass m, on its linear path at any instant, an imaginary point P is supposed to be rotating in a circle, always keeping vertically above the oscillating particle. The path of this imaginary point is called *the circle of reference*. If we assume that the reference point P is moving along the circumference of the circle at a constant speed, then particle m is oscillating along the diameter with simple harmonic motion. At any one time, the angle of rotation is also a measure of the position of the reference point P on the circumference of the circle. Similarly, the position of particle m at any one time is also a function of the angle of rotation. The relationship between the displacement of particle m and the angle of rotation is basic to the formulation of simple harmonic motion. It can be easily demonstrated that displacement or amplitude, velocity, and acceleration, as well as the restoring force acting on particle m at any time, are also a function of the angle of rotation. The harmonic motion induced in a vibrating body depends for its *transmission* and *propagation* upon the surrounding *medium*—liquid, solid, or gaseous.

The phenomenon of sound, perceived by the human ear, is a specific instance in which the harmonic motion of a vibrating body is transmitted through the medium of air, received by the ear drum, and interpreted by the synthetic and analytic powers of the brain. Evidently, the harmonic motion of the source must be accurately *reproduced* and propagated in the conducting medium, in order to be faithfully perceived or registered.

Speed of Sound. The transmission of a wave through a segment of the medium over a specific distance requires a certain amount of *time*. The *amount of time*, i.e., the time consumed by the wave in propagating across a specific distance, is determined by the elasticity and density of the medium. Since density is, by definition, mass per unit volume, the heavier the particles of the medium, the greater the density, and consequently the more difficult to move them. The velocity of propagation is then correspondingly less. On the other hand, the greater the elasticity of the medium, the more easily are the particles displaced and the more rapid the propagation. *The speed of sound is, therefore, inversely proportional to the density of the medium and directly proportional to its elasticity*, or

$$c = \sqrt{\frac{E}{\rho_0}}$$

where E = elasticity
ρ_0 = density

The speed of propagation in a given medium, under given conditions, is independent of frequency. Since the wavelength is the distance covered in one period of time, namely, the time required for the completion of one cycle, it is evident that *the cycle length or wavelength must necessarily vary inversely with the frequency*, or

$$c = \lambda f$$

where c = speed of sound
λ = wavelength
f = frequency

For a given frequency, the wavelength varies directly with the speed of propagation for different media.

Pure Tone. The term "pure tone" is generally applied to wave motion generated by a source vibrating harmonically with a single, definite frequency. A pure tone is defined physically if the

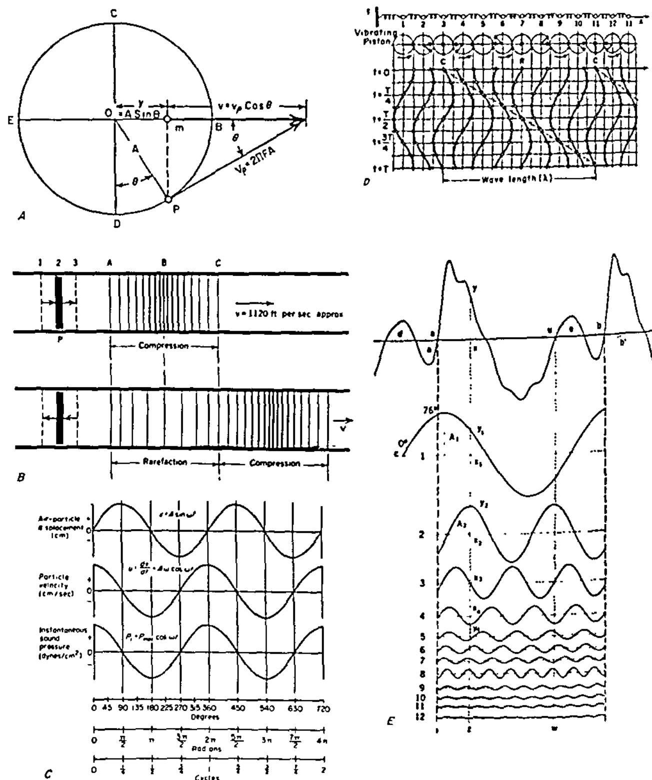


Fig. 3-41. A. Simple harmonic motion as analyzed and illustrated through the circle of reference. The displacement and velocity of particle *m* at a point corresponding to angle θ (theta) of rotation, is graphically and mathematically represented. B Longitudinal (compressional) sound wave generated by piston *P*, oscillating harmonically, is schematically represented. As the piston moves from 1 to 3, it compresses the air with the greatest effect at the central point 2. At this point, the displacement is minimal while the velocity is maximal. The opposite effect (rarefaction) is produced as the piston moves in the opposite direction. C. When successive values of displacement, velocity, or pressure in a harmonically moving body are plotted against time or the angle of rotation (in degrees or radians), sine waves result that define the phase and magnitude of each quantity Pressure and velocity, being in phase, are maximal when displacement is minimal D. Diagrammatic

basic variables by which it is differentiated from other tones are specified. These variables are three-dimensional and include magnitude, frequency, and phase.

Frequency is determined by the number of cycles per second (cps) through which a vibrating body is oscillating, while the *period* is the time required for the completion of one cycle. The physiological counterpart of frequency is *pitch*. It is dependent mainly, though not entirely, upon the

periodic quantity, or complex wave, is therefore the lowest component frequency. A component with a frequency twice that of the fundamental is called the second harmonic. *Harmonic frequency* is therefore defined as the frequency of a component in a periodic wave, which is an integral multiple of the fundamental frequency.

The term *overtone* denotes a frequency component in a complex wave which, though higher than the fundamental, may or may not bear an integral relation to that frequency. An *octave* is the interval between the fundamental frequency and the second harmonic, or any two notes of frequency ratio 2:1. *Phase* determines the relationship between two sine waves with respect to time. When two sinusoidal waves are coincident at all times, they are said to be "in phase." When one precedes, they are out of phase. The preceding wave is said to be "leading," the other "lagging." Determination of the amount of lead or lag in degrees is essential if a sinusoidal wave is to be defined. *Magnitude* can be specified in any one of four terms: displacement, velocity, pressure, and intensity (Fig. 3-41C).

The *displacement* of particles in a longitudinal (compressional) wave is in the direction of wave motion. Since the particles are displaced sinusoidally from an average position of rest, the magnitude of a pure tone can therefore be specified in terms of particle displacement, being directly proportional to the latter value.

The *velocity* of an oscillating particle can similarly be used to specify the magnitude of a pure tone. Particle velocity is 90° out of phase with displacement, so that velocity is maximal when the displacement is minimal.

The *pressure* generated in a medium, following the propagation of a pure sinusoidal wave, presents a third and a most important term through which a pure tone can be defined physically. Furthermore, of the four terms through which magnitude is defined, pressure offers the most convenient and readily available measurable variable that lends itself to immediate transduction through a microphone. The instantaneous sound pressure at a point can be defined as the excess pressure at that point over the static pressure. The unit of sound pressure is the *microbar*,[5] which is equivalent to dyne/cm².[6]

The *intensity* of a sinusoidal wave motion is a function of both pressure and velocity. It may thus be considered a more comprehensive measure of magnitude. However, since pressure and velocity are related, a quantitative definition of intensity must await the elucidation of this basic relationship.

Pressure–Velocity Relationship in a Compressional Wave. The propagation of a compressional wave through a medium results in a transient disturbance of the pressure–density relationship, on the one hand, and of particle velocity, on the other. The compressional wave, by creating an area of increased pressure, brings about a corresponding increase in density. Particle motion is a corollary of the sinusoidal nature of the pressure wave. In its totality, the phenomenon of wave propagation can be formulated in terms of three variables, i.e., velocity, pressure, and density. The equation of pressure with which we are concerned is actually a specific formulation of the fundamental gas law. So that if ρ_0 = normal density, p = excess pressure, c = speed of sound, v = particle velocity

then
$$p = \rho_0 c v \qquad (1)$$

The above relationship maintains that excess pressure resulting from a compressional wave is directly proportional to particle velocity. ($\rho_0 c$ may be considered constant for a given medium under specific conditions.) Evidently, the relationship of pressure to velocity differs with different media. Implicit in the above relationship, however, are two other principal variables with which we are

[5] Some authors refer to this unit as the bar; however, this usage is deprecated in the American Tentative Standards.

[6] A dyne is defined as the force which, acting on a mass of one gram for one second, produces an acceleration of one centimeter per second per second.

presentation of the successive positions of an air particle as the sound wave is transmitted through the medium. The displacement, direction of motion, velocity, etc., are thus inferred from the respective hypothetical circle of reference. As the wave is propagated to the right, i.e., as time goes on, the oscillating particle, moving harmonically, assumes a new position as indicated by the successive horizontal lines. E. Harmonic analysis of a complex waveform. (C, from Hirsch, Measurement of Hearing, McGraw-Hill, 1952; others, from Watson, Sound, Wiley, 1935.)

concerned for a quantitative analysis, i.e., amplitude, or displacement, and frequency. The maximum velocity can be readily shown to be

$$V_{max} = 2\pi fA$$

where f = frequency
A = amplitude (maximum displacement)

The amplitude in terms of velocity is readily derived from the above as

$$A = v_{max}/2\pi f$$

For a constant maximum velocity, then, the amplitude (or maximal displacement) of the oscillating particle is inversely proportional to frequency. As the maximum particle velocity is synchronous with the peak of the pressure wave, i.e., they are in phase, the maximum pressure in terms of maximum velocity can also be written as

$$p_{max} = 2\pi fA\rho_0 c \qquad (2)$$

In other words, an increase in amplitude is evidence of greater pressure. Similarly, for the same amplitude, a higher frequency is suggestive of greater pressure. In terms of pressure and frequency, the amplitude is equal to

$$A = p_{max}/2\pi f\rho_0 c \qquad (3)$$

For a constant pressure, therefore, an increase in frequency results in decreased amplitude.

Intensity. The concept of intensity is basic in the appraisal of wave motion. It constitutes, beside particle velocity and pressure, a third and more inclusive dimension by which the magnitude of a sound can be measured. *As used in wave motion, intensity is synonymous with power*, as applied in mechanics, and analogous to power, as used in electricity. Power can be defined as the rate of doing work, work, however, means the overcoming of an opposing force, and always implies the movement of a body against a force that opposes the movement. *Energy*, on the other hand, is the ability to do work or the capacity for doing work. Theoretically, the energy stored or expended by a mass, wave, or electrical charge, is numerically and dimensionally identical with the work done by, or transferred to the mass, wave, or charge. From the above, the following relationships are self-evident:

Work (ergs) = force (dynes)
× distance (cm) – – Mechanics

Work (volt-coulombs) = voltage (volts)
× charge (coulombs) – – Electricity

Work (ergs/cm^2) × amplitude (cm) – – Acoustics

The conversion values of the different energy units are as follows:

10^7 ergs = 1 joule = 1 volt-coulomb =
1 watt-second

Power or intensity is defined by the following relationships. In each instance, power depends upon the amount of work done and the time required to do it:

Power (ergs/sec) = force (dynes)
× velocity (cm/sec) – – Mechanics

Power (watts) = voltage (volts)
× current (amperes) – – Electricity

Intensity (ergs/cm^{2}sec) = pressure (dynes/cm^2)
× velocity (cm/sec) – – Acoustics

If electrical units are used to express the power or intensity of a sound, instead of mechanical units, then:

$$\text{Intensity} = \text{watt-sec/cm}^2\text{sec} = \text{watt/cm}^2$$

The intensity of a sound may now be defined as the energy that flows through a unit area per unit of time. In a gas of density ρ_0 for a plane or spherical wave having a velocity of propagation c, the sound intensity I corresponding to a pressure p is given by the following equation:

$$I = p^2/\rho_0 c = v^2\rho_0 c \qquad (4)$$

This relationship becomes evident by substituting for v and p in the basic pressure–velocity equation, since

$$p = \rho_0 cv \quad \text{and} \quad v = p/\rho_0 c$$

Evidently, the intensity varies with the square of the pressure or the velocity; so that a doubling in pressure or velocity results in a quadruple increase in intensity provided the impedance c remains constant. Furthermore, since, as demonstrated earlier, the maximum pressure of a sinusoidal wave is also related to the maximum velocity, as well as the frequency and amplitude (Eq. 2), the maximum intensity of a sinusoidal wave can be expressed in the following terms.

$$I_{max} = v^2_{max}c = (2f)^2(A)^2c \qquad (5)$$

which is equivalent to saying that the intensity varies with the square of the frequency and the square of the amplitude. Thus, if the amplitude of a wave is to remain unchanged, *doubling the frequency results in a quadruple increase in intensity.* Similarly for a given frequency *a twofold increase in amplitude results in a fourfold increase in intensity.* On the other hand, if the intensity is to remain constant, both pressure and velocity should remain constant. However, under the circumstances, *a doubling of the frequency will be reflected by a reduction in the amplitude to one-half the original value.* Vice versa, a fourfold increase in amplitude will have to result in a corresponding decrease in frequency if the intensity is to remain constant. The preceding relationship is

particularly rewarding, since it defines all the measurable variables in a sinusoidal wave, including intensity, pressure, velocity, frequency, and amplitude.

Scale of Measurement. An electroacoustical system involves by definition the conversion of acoustical into electrical variables, and vice versa. The vibratory and electrical measurable elements, however, cover an enormous range of frequencies and magnitudes. The representation of these large ranges of numbers on *linear scales* has proved to be inconvenient and difficult to handle. The familiar linear scale, where successive values are obtained by the simple process of adding 1s, therefore, unsuitable for this purpose. The *logarithmic scale* circumvents this difficulty by substituting a unit which is the successive multiple of a number called the *base* (usually 10).[7] Such a scale, though linearly divided, actually indicates a logarithmic increase, since the successive units *represent the* powers to which the base has been raised.

The Bel and the Decibel. The ratio of the power or intensity of an accentuated 1st to an attenuated 2d heart sound, may at times be in the vicinity of 10,000:1. Such figures are cumbersome to handle. As stated earlier, a more convenient way of writing the ratio would be 10^6:10^1. However, since the base is generally understood to be 10, the ratio can be further simplified by including the exponent alone, i.e., 6:1 or 6. The unit of the resultant number, 6 in this case, is the *bel*, which, stated differently, *is the ratio of the exponents of two powers*. The bel is defined as the fundamental division of a logarithmic scale for expressing the ratio of two quantities of power. The number of bels denoting such a ratio is the logarithm to the base 10 of *this ratio*. Mathematically expressed, the ratio of two powers in bels is expressed by the following formula:

$$N \text{ (in bels)} = \log_{10} P_1/P_2 \quad \text{or} \quad P_1/P_2 = 10^N$$

As the value of the bel is too high for practical sound measurements, the term *decibel (db)* was introduced to represent *one-tenth* the power ratio in bels. Expressed in decibels, the ratio of two intensities or powers would be:

$$n \text{ (in db)} = 10 \log_{10} P_1/P_2$$

The Concept of Level. Since there is a logarithmic scale of measurement based on the ratio of two values rather than on absolute values, it is only logical to proceed further and adopt a standard level having a fixed absolute value. All terms would then be compared to the standard level, and their values in decibels could then be assessed with reference to the standard level.

Reference Intensity. Intensity Level. The standard level taken to represent zero or reference intensity of sound has been internationally adopted to correspond to the intensity of a tone of 1,000 cps, which is only barely audible. This threshold value of a just perceptible intensity has been standardized as an intensity equivalent to 10^{-16} watt/cm². The intensity level of a sound in decibels is the ratio of the intensity I of this sound to the reference intensity of 10^{-16} *watt/cm²*.

$$\text{Intensity level (in db)} = 10 \log I_x/I_{ref}$$

Reference Pressure: Sound Pressure Level. The reasoning employed in developing the concept of reference intensity could be applied equally well if pressures are to be compared. The pressure that *corresponds to* the reference intensity of 10^{-16} watt/cm², can be calculated from the pressure formula. It is found to be equal to

$$2 \times 10^{-4}\ \mu\text{bar}$$
$$= 2 \times 10^{-4}\ \text{dyne/cm}^2 = 0.0002\ \text{dyne/cm}^2{}^*$$

This is the *reference* or *zero level of pressure used in determining the sound pressure level*, which is:

Sound pressure level

$$= 20 \log_{10} P_x/0.0002 \quad \text{dyne/cm}^2$$

The coefficient is naturally 20, for the log of any number squared is equal to 2 times the logarithm of the number since

$$10 \log_{10} P_x^2/P_{ref}^2 = 2 \times 10 \log P_x/P_{ref}$$

ANALYSIS OF COMPLEX WAVES

All periodic complex waves (be they pressure waves, cardiograms, ballistocardiograms, or phonocardiograms) can be analyzed and separated into harmonic components of the fundamental frequency if the sample tracing is long enough to be considered as extending to infinity. The fundamental frequency (known as "the period"; see Fig. 3-41E), as already stated, is equal to the reciprocal of the duration of the basic pattern of the waveform. As such, harmonic motion can be considered as a basic physical phenomenon. It must be stressed that, no matter how complex a waveform is, as long as it is periodic, it gives rise to a discrete set of frequency components or *har-*

[7] The logarithm of a number to any base is the exponent of the power to which the base must be raised to equal the number, so that

$$x = \log_a y \quad \text{if and only if} \quad y = a^x$$

The choice of the base is an arbitrary matter. In electronic work, the base 10 is often employed.

* A commonly used reference pressure is the dyne/cm² or the microbar (μbar). The present level of 0.0002 μbar is 74 db below the reference pressure.

monics Of course, a truly periodic waveform is so shaped that any basic repetitive pattern can be superimposed and exactly matched to any other.

The representation in terms of harmonics is by no means unique. There are other combinations of waveforms that can be added up to form the original one. However, the representation in terms of harmonics (or sinusoidal components) is the most convenient and probably closest to physical reality because these sinusoidal components are the only waveforms that preserve their shape after going through a linear system, whether physiological, mechanical, or electrical.

Periodic waveforms can then be represented as a discrete set of sinusoidally varying frequency components. These components are integral multiples of the fundamental or lowest frequency component When the set of frequency components of a periodic function, which varies with time, is plotted on a frequency scale, it is known as a *line spectrum* (Fig 3-42A).

If the periodic waveform is measured over a finite extent (a limited number of cycles), then it is no longer truly periodic, and new frequency components (*overtones*), not integral multiples of the fundamental, will be introduced. The relative amplitudes of these overtones, as compared to the harmonics, will be small if the measurement involves a large number of cycles In practice, no measurement is made over an infinitely long waveform; however, it is long enough to give close approximation to a line spectrum. The fewer cycles in the tracing, the more significant will be the overtones, and the spectrum will be continuous

When random noises (extraneous vibrations) are superimposed, they will destroy the periodicity of the waveforms, so that no two basic patterns will be exactly alike; the frequency spectrum will then contain a significant number of overtones The resulting spectrum will obviously be continuous. If the noise is small, the repetitive character of the waveform will still predominate.

Although the pattern of two successive heart beats will not be exactly identical, the repetitive character is close enough to a truly periodic waveform, so that its *frequency spectrum* can be con-

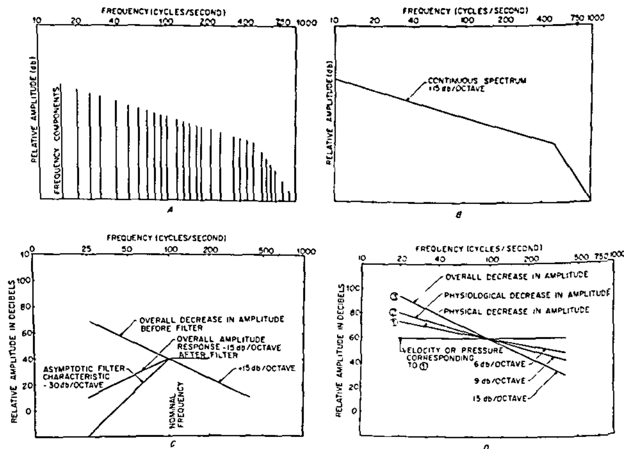


Fig. 3-42. A. Scheme of the line spectrum of frequency components comprising the vibrational phenomena at the surface of the chest wall B Scheme of continuous spectrum corresponding to the line spectrum of (A). C. Simplified scheme of the attenuation characteristics of a filter, as applied to a band with a nominal frequency of 100 cps. D. 1, Decrease in amplitude with increase in frequency for constant intensity, pressure, or velocity. 2 and 3, Physiological and over-all decrease in amplitude with increase in frequency.

sidered a *line spectrum* for practical purposes, *the heart can then be considered as a generator of harmonics*

CARDIOGRAM AND PHONOCARDIOGRAM

If the displacement of the chest wall over the cardiac area is reproduced with perfect fidelity, the resultant tracing reveals *a complex waveform* (Fig. 3-41E). When the registration is restricted to any one area, the complex wave is then known as the "cardiogram" In effect, such a complex waveform, repeating itself periodically with the heart beat, represents the *additive result* of a finite number of pure sinusoidal waves of different amplitudes, frequencies, and phases. Stated differently, if the sinusoidal waveforms of the individual frequency components are superimposed, the periodic complex waveform constituting the cardiogram can be accurately constructed by their simultaneous addition (Fig 3-41E).

The *fundamental frequency* of the cardiogram, i e, the frequency of a period equal to the whole complex wave, is necessarily that of the heart rate Each of the other frequencies incorporated in the cardiogram is, therefore, an integral multiple of this fundamental frequency. It is apparent that the energy content of the cardiogram is equivalent to the total energy appearing across the chest wall, since it incorporates the energy level of all the components *Harmonic analysis* of the complex waveform, i e, the breaking up of a periodic complex wave into its individual components, is therefore essential, if the phenomenon recorded by the phonocardiogram is to be appreciated in its totality, as well as its frequency and intensity relationship (Fig 3-41A). Employing a special electronic device, the cardiogram can be split into its individual sinusoidal components. If these components are graphically represented as to their frequency and intensity, a *line spectrum of the total vibrational phenomenon results* The position of each individual vibration along the abscissa determines its frequency, while its height is a measure of its intensity. Such a spectrum, as constructed from available published data, is presented in Fig. 3-42A.

In regard to *frequency*, the vibrational spectrum comprising the cardiogram can be arbitrarily subdivided into two main adjacent bands (Fig. 3-43A); since the lower limit of auditory perception is generally considered to be 20 cps, this frequency is taken as the dividing line between the *audible bands* and those which, the authors suggest, should be called *infrasonic bands* of the vibratory spectrum The *ballistic band*, comprising the lowest frequency components in the infrasonic band, incorporates the major part of the vibrational energy. This is better appreciated if it is remembered that the ballistic band is the one largely responsible for the visible and palpable effect of *the apex beat* (Fig. 3-43B). The audible band of the spectrum, extending from 20 to 1,000 cps, encompasses the greatest number of individual frequencies while the energy content of its components is definitely less than that of the ballistic band.

The intensity level of the frequency components bears a variable and interesting relationship to the threshold of audibility. The *threshold of hearing*, against which the decibel yardstick is laid, is the lowest level at which the normal ear can perceive the various tones *throughout* the frequency range from 20 to 20,000 cps The ear is more sensitive to frequencies ranging from 800 to 5,000 cps. This means that it can detect a much fainter sound in this range than in the higher or lower areas. Accordingly, a tone of 64 cps must be 50 decibels (db) or 100,000 times as powerful as a tone of 1,000 cps to seem equally loud. At the upper and lower limits of the frequency range, the intensity must, therefore, be increased enormously above that required for the reference tone of 1,000 cps (Fig. 3-47).

Based on the preceding description, the frequency components comprising the audible band can be subdivided into three adjacent bands in respect to their relationship with the threshold of audibility (Fig. 3-43A). The first band, extending from 20 to 40 cps comprises *vibrations of high intensity*, though of lesser magnitude than the infrasonic (or ballistic) components. Nevertheless, the energy level of these vibrations *is not* sufficient to compensate for the extremely low sensitivity of the human ear in this range. *This band is therefore inaudible*, unless the sounds acquire tremendous magnitude caused by pathological phenomena An example is presented by certain diastolic sounds (3d sound, 4th sound) which often arise in diastole in the flabby musculature of

patients with coronary heart disease. These sounds are in the range of 30 cps and may be heard as dull thuds (or give the impression of an indistinct rumble) if they are of sufficient magnitude.

The second band, extending from 40 to 750 cps, comprises components of still lower magnitude. However, as the threshold of hearing over this band *is* high, i.e., the ear is more sensitive, these frequency components are perceived by the normal human ear and constitute the *audible portion of the vibrational spectrum*, namely, the *heart sounds*. Even though this is the really sonic band, vibrations of the same magnitude will be heard louder and louder, if they are of increasing frequency, because of

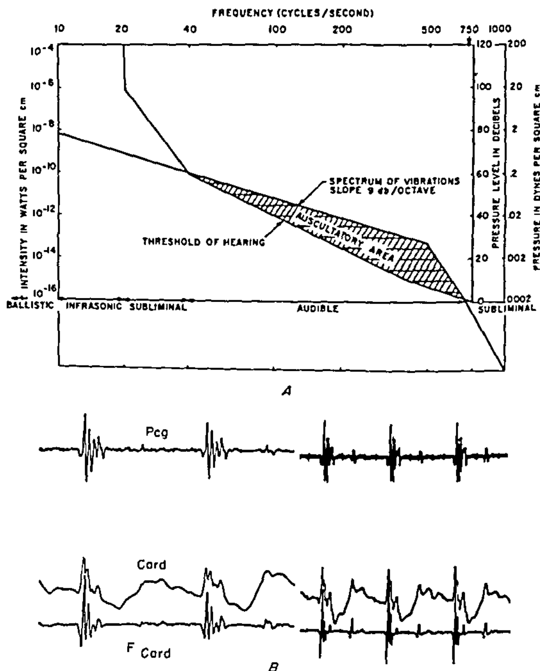


Fig. 3-43. A. Relationship of the vibrational spectrum to the threshold of hearing. B Cardiogram and phonocardiograms of a normal young man. The cardiogram is recorded at the apex by means of a "linear" microphone. *Pcg.*, Regular phonocardiogram from same area using a crystal microphone; *F, Card.*, phonocardiogram derived by filtering (attenuating) the output of the linear microphone for vibrations below 60 cps and above 110 cps, using band-pass filters, then amplifying the filter output. The two lower tracings are thus derived from the same microphone (at left: paper speed of 100 mm/sec; at right: paper speed of 50 mm/sec).

the logarithmic scale with which the auditory system of man perceives sounds.

Above the range of 750 cps, the vibrations are of minimum intensity. Despite the excellent sensitivity of the ear to this range, *these components may not be audible since they fall below the minimal intensity required for threshold perception* An exception is presented by certain pathological *clicks* (or *snaps*) or by rare *high-pitched murmurs*, which can give audible vibrations in this range (Fig. 3-43A).

Thus, of the total vibrational spectrum appearing on the surface of the chest wall, only a limited band lends itself to auditory perception. What the average listener hears in the auscultation of the heart is, therefore, restricted to the above-mentioned band Evidently, auscultation is far from being an ideal instrument for the assessment of the total range of vibrations.

Intensity Level of Vibrational Spectrum. In the above discussion, the intensity level of the individual frequencies was pointed out as mainly dependent on its position in the different bands Furthermore, the decrease in the intensity level of the successive bands was noted However, no attempt was made to formulate the intensity relationship of the various frequencies within the line spectrum Such a relationship is essential, as will be apparent later, if the vibrational phenomena are to be registered and quantitatively studied.

If the intensity levels of the frequency components forming a line spectrum (Fig 3-42A) are joined together, the sloping line that results is called *the continuous spectrum* (Fig 3-42B) It represents all possible combinations of the frequency components that may be encountered The slope of such a line, on the other hand, represents *the decrease in the intensity level of the frequency components with increasing frequency* When plotted on a logarithmic scale, the slope of such a line can be specified in terms of decreasing intensity level in decibels per octave The intensity level of the vibrational spectrum appearing at the surface of the chest in man was found to decrease at the rate of 6 to 12 db/octave increase in frequency,* the average being 9 db/octave Stated differently, frequency components at 200 cps are found at an intensity level which is, on the average, 9 db lower than the intensity level of those components at 100 cps

Mathematically expressed, the intensity of the vibrations can be said to vary inversely between the first and second power of the frequency, so that pressure varies from $1/f$ to $1/f^2$. In the first instance, the slope would be 6 db/octave, corresponding to an amplitude ratio of 2:1 while, in the second, the slope would decrease at the rate of 12 db/octave increase in frequency corresponding to an amplitude ratio of 2^2:1 or 4:1.

In the marginal bands of audibility, sounds can be perceived only if their intensity is great enough to affect the receptors of the auditory system Whenever they are below the threshold of hearing, they will not be perceived, even though their frequency is within the audible range. The authors suggest the term *subliminal vibrations* for such frequencies (Fig 3-43A)

Phonocardiography. Phonocardiography is generally thought to be almost synonymous with the graphic registration of the auscultatory phenomena as perceived by the human ear However, since the vibrational spectrum at the surface of the chest constitutes a single uninterrupted physical phenomenon, it is suggested by the authors that phonocardiography be defined as *the graphic recording of the total spectrum of vibrations with or without selective attenuation of any one band.* As such, phonocardiography is meant to include (1) the registration of the ballistic and infrasonic band; (2) the subliminal sounds of the audible band, and (3) the audible components of the audible band However, no system of phonocardiography can be devised that can simultaneously register all these bands with equal clarity and detail Therefore, it is necessary to attenuate the ballistic and infrasonic bands if the audible band is to be registered and analyzed, or, vice versa, to sacrifice detailed definition of the audible band if an exact transcription of the ballistic band is desired

The Problem of Recording. The intensity level of the individual frequencies, revealed through harmonic analysis of the vibrational spectrum, covers a dynamic range of 100 db. A vibration in the *sonic* band may vary from 1 to 10,000 times in intensity. The human ear is well suited to cope with such a range of intensities because a logarithmic increase in

* $20 \log P_1/P_2 = 20 \log 2^2/1 = 20 \log 4 = 12$ db

intensity is perceived as a linear increase. Then, a tenfold increase in intensity (10 db) is felt as a twofold increase in loudness and, therefore, is still within auditory range. This being the case, the dynamic range of the ear extends over 130 db, the dynamic range of the cardiac vibrations within the audible band being well within the dynamic range of the ear. Graphic registration of the same phenomena, however, can only be accomplished on a linear scale. As the transducer is made to respond linearly to various intensities, the voltage generated varies directly with the intensity of the frequency components. The final record then represents faithfully, i.e , on a linear scale, the intensity level of the various frequencies. The maximum dynamic range that can be safely covered by such a system for accurate and detailed analysis does not exceed 50:1 but the dynamic range of the frequency components may extend as high as 1,000,000:1, the impossibility of such a record is evident. Thus, then was the dilemma that confronted the early workers in phonocardiography. no system can possibly yield an exact graphic record of all vibrations and, at the same time, reproduce the high-frequency, low-intensity vibrations with clarity This is because the low-frequency vibrations are of so great an intensity as to dominate the record almost to the exclusion of the high-frequency components, which appear as tiny notches superimposed on the giant waves. Greater amplification is naturally precluded by the width of the paper. Such a tracing, however inadequate for the study of the high-frequency components of the audible band, is, nevertheless, *linear* and represents accurately the complex wave resulting from the simultaneous addition of the frequency components of the spectrum For this reason, whenever one is interested in obtaining a faithful reproduction of the apical thrust or other pulsation of the chest, one uses a "linear" system of registration Any attempt to register with clarity and detail the high-frequency, low-intensity elements, *necessarily involves the attenuation of the low-frequency components* For a quantitative appraisal of the attenuation involved, a brief outline of the apparatus is essential.

Apparatus. Essentially the phonocardiograph is an electronic device for converting the energy content of the vibrational spectrum into voltage, which is then amplified and made to drive a recording device. It consists essentially of four different parts, the relative characteristics of which are responsible for the type and accuracy of the final record. The four parts are the transducer, the filter, the amplifier, and the galvanometer. The four parts will be considered separately.

THE TRANSDUCER (MICROPHONE). This is the critical element of a phonocardiograph, since it is the device employed for the conversion of the primary mechanical vibrations into electrical impulses. Of the four measurable dimensions of a sinusoidal wave, i e., displacement, particle velocity, pressure, and intensity, pressure and particle velocity are the simplest quantities to transform and, therefore, to record. On the other hand, if the microphone is to be a perfect transducer, it is essential that its electrical output be a faithful, undistorted image of the sound pressure acting on it. Accentuation or attenuation of any one frequency can only result in a distorted picture of the phenomenon under study. Of the available microphones, the crystal and the dynamic microphones are those most commonly used in phonocardiographic studies.

The action of the *crystal microphone* is based on the piezoelectric properties of certain crystals, in that electric potentials are set up when pressure is applied to one face of the crystal If pieces of metal foil are placed on each side of the crystal, a difference of potential is generated between them When such a crystal plate is placed between a fixed plate and a diaphragm which is brought into motion by the wave pressure, an electromotive force (emf) is generated, which is proportional to the deflection of the diaphragm (displacement), which in turn is a function of the pressure applied

In the *dynamic microphone*, the diaphragm brought into motion by the vibration carries a conductor which is placed in a constant magnetic field As a result of the movement of the conductor within the magnetic field, an emf is developed which is proportional to the velocity of the diaphragm deflections.

Amplitude of Deflection as a Function of Frequency for Constant Pressure and Velocity. Given two vibrations of equal pressure, e g , 100 cps and 200 cps, the amplitude (displacement) of the highest is one-half that of the vibration of the lowest.

The vibration of higher frequency completes a full cycle in one-half the time required by that of lower frequency. The particle velocity is necessarily the same for both. The pressure being equal, the amplitude of vibration is inversely proportional to the frequency while the velocity is independent of the frequency. This is demonstrated in Fig. 3-42D, in which the horizontal line represents the velocity or pressure while the sloping line 1 indicates the amplitude. Translated into db, the amplitude of a wave can be shown to decrease at the rate of 6 db/octave for constant pressure. Line 1 then is the fundamental response characteristic of the crystal microphone, while the horizontal line is the response characteristic of the dynamic microphone. Line 2 is the natural decrease in amplitude of the vibrational spectrum, independent of frequency, while line 3 is the total frequency-dependent decrease in amplitude.

THE FILTER. The filter is the decisive factor in determining the response characteristics of any system of phonocardiography, or any channel or band within a certain system. Essentially, *the filter determines the extent and degree of attenuation of the vibrations included in a certain range.* Filters consist of capacitors and resistors or capacitors and chokes; simply by varying the value of these components, any degree of low- or high-frequency cut can be obtained. A filter can be made to attenuate anything below (*high-pass filter*) or anything above (*low-pass filter*) a certain frequency. The attenuation characteristics of a filter can be quantitatively regulated to represent a definite value of attenuation, usually measured in decibels/octave increase or decrease in frequency. As such, the characteristics of a filter can be represented by a line the slope of which is identical with the attenuation value. Given the cutoff frequency of a filter, the degree of attenuation to which a certain frequency band is subjected can be accurately foretold. It is apparent that, if the spectrum of vibrations between 1 and 1,000 cps is to be divided into limited bands, a high-pass filter should be incorporated into the system. The characteristic of the final record becomes a function of the cutoff frequency, as well as of the slope of the asymptotic filter characteristic. Since the vibrational spectrum attains a decrease in amplitude of 15 db/octave with increasing frequency, the incorporation of a high-pass filter with a sharp slope actually reverses the natural slope of the vibrations, so that, at the cutoff frequency, the vibrations are recorded with the greatest amplitude. This frequency is called *the nominal frequency* of the band in question. A simplified diagram of the filter action is given in Fig. 3-42C.

The committee on Standardization of the Phonocardiogram has put forth several recommendations including suggestions for the standardization of the filter slope. However, no two systems throughout the world have similar characteristics. Under such circumstances the records are not exactly comparable. All systems, however, include at least two separate bands with different response characteristics while some include as many as seven different bands including one with a frequency response which simulates the typical response of the human ear. Furthermore, though the bands in the different systems are not exactly similar, the records are roughly comparable, for the corresponding bands.

A satisfactory scanning of the vibrational spectrum (excluding the ballistic band) requires at least three separate and adjacent bands for recording the frequency components of the *infrasonic, subliminal,* and *audible bands.* A fourth, higher, band would permit special clinical studies.*

Band 1 should have its maximum sensitivity between 12 and 35 cps. At such a frequency (the nominal frequency) the response is maximal in terms of amplitude or deflection. The elements of higher frequency, though capable of passing the filter barrier, are of such low intensity compared with the great intensity of the low-frequency vibrations, that they cannot be seen on these records. The final picture can hardly be expected to resemble any visual representation of the sound. This band would grossly correspond to the low-frequency response of Leatham.

Band 2 is chosen with a nominal frequency between 50 and 100 cps and would correspond to the medium-frequency response of Leatham and the "stethoscopic" response of Rappaport and Sprague.

The maximum sensitivity of *band 3* is adjusted at a frequency of 200 to 240 cps. In this band, the low-frequency, high-intensity elements are sharply attenuated, allowing maxi-

* The apical thrust and other ballistic, low-frequency vibrations of the chest wall are recorded best by means of a "linear" transducer.

mal amplification for the registration of the high-frequency elements.

The use of a band-pass filter comprising a high-pass and a low-pass filter (as advocated by one of the authors) would permit scanning the vibratory spectrum in separate, adjoining bands, thus allowing a better definition of any particular vibration within each frequency band Moreover, this arrangement would help in decreasing the "noise" level.

The authors suggest setting the band-pass filter (high-low pass filter) having a 24-db attenuation at the following minimum and maximum frequencies, respectively: (1) 15 to 30, (2) 30 to 60, (3) 60 to 120; (4) 120 to 240, (5) 240 to 480; (6) 480 to 1,000. Band I would be useful in the study of infrasonic and ballistic vibrations Bands 2, 3, and 4 are those which have the greatest clinical interest. Bands 5 and 6 would be used for special clinical studies or in particular cases

THE AMPLIFIER. The various electrical potentials, as generated at the microphone and modified by the filter, pass into a vacuum-tube amplifier, where the degree of amplification is regulated by a volume-controlling device The amplifier should be free from internally generated noise The relative silence of the valve constitutes a limiting factor for maximum amplification, since fuzziness of the base line can easily be misinterpreted Furthermore, as the output of the microphone may be as low as 3μ volts for the high-frequency, low-intensity vibrations, the amplifier should have enough gain to project the signal with sufficient amplitude and without undue distortion of the base line.

THE GALVANOMETER The response of the galvanometer should be flat from 0 to 1,000 cps. As the deflection of the galvanometer is a function of the voltage across the coil, and since the voltage output of the transducer has been shown to be proportional to the pressure of the individual frequencies, the displacement of the beam (i e, the extent of deflection) is also a function of the frequency As was shown in the case of the diaphragm of the microphone, the deflection of the beam decreases at the rate of 6 db/octave with increasing frequency for constant pressure Thus, given two waves of the same intensity, the deflection of the beam will be smaller for waves of a higher frequency. Although the most ingenious devices have been invented in an attempt to replace the mirror galvanometer and the photographic paper with an equally sensitive direct-writing galvanometer, the photographic or mirror galvanometer is still the most accurate and satisfactory, as to sharpness and detail of the record, as well as permanency.

Technique. The vibrations transmitted to the chest wall by the dynamic action of the heart beat vary in frequency from 1 to 1,000 cps. i.e, from the grossly palpable to the faintly audible. In the low-frequency range, they are of high intensity or amplitude; in the high-frequency range they are of low intensity or amplitude. The selective and differential reproduction and registration of these vibrations by the phonocardiogram is a function of the physical properties of these vibrations as well as of the recording system. The range of the normal vibrations constituting the vibrational spectrum has already been discussed. The *1st and 2d heart sounds* are actually periodic pulses consisting of a finite number of frequency vibrations distributed along the vibrational spectrum. The intensity distribution among the frequency components, however, follows the energy distribution along the spectrum While certain vibrations are in the range between 20 and 60 cps, several are between 60 and 120, and a few overtones are between 120 and 240. Components of even higher frequency can be found in them, especially in the 2d sound The *3d* and *4th heart sounds* are largely composed of vibration in the range of 20 to 60 cps. *Diastolic rumbles* cover the range of 40 to 140 cps. However, the presystolic murmur of mitral stenosis may have important components in the range of 120 to 240 cps. Systolic murmurs extend over a wide range depending on their characteristics. When accompanied by a thrill, a *systolic murmur* has components in *the low-frequency band of 40 to 100* cps. The soft systolic murmurs, however, cover a band extending from 200 to 400 cps. The *early-diastolic murmur* of aortic insufficiency is usually composed of high-frequency elements extending all the way up to 1,000 cps. In the majority of cases, a sound or murmur is recorded the best in that band in which its most intense vibrations are located, while adjacent bands reveal the range of the frequency components and their relative intensity.

It is apparent that the desired effect, in the

final record, can be produced by the calculated integration of the intensity and frequency characteristics of the sounds or murmurs and the characteristics of the frequency response of the apparatus Good technique, then, requires a rough appraisal of the frequency characteristics of the sounds or murmurs under consideration, as well as a thorough familiarity with the limitations and potentialities of the apparatus as a whole, and of the different bands By repeated experience, the distortion or fidelity of the final record in relation to the auditory impression can be fairly accurately anticipated, and the desired accentuation or attenuation of certain elements obtained with the aim of overcoming the various auscultatory problems that may arise from the inherent limitations or deficiencies of the human ear itself.

Phonocardiographic technique, therefore, is not a process of trial and error, with the desired record obtained through chance selection, nor is it a matter of routine application of a standard technical maneuver. *Phonocardiography is actually a technique of selective or differential transcription which could be compared to a selective auscultation if the human ear had a wider (lower) range and a linear type of response.* It is thus in relation to problems arising from auscultation that phonocardiographic technique derives its importance, in the sense that *it actually represents a technical method of selectively improving on the human ear and thus reducing the problem to a factual analysis of a permanent record.* The manual techniques of manipulation of the apparatus, adjustment of the proper frequency and intensity, and location and application of the microphone are of practical, though secondary, importance

CLINICAL PHONOCARDIOGRAPHY

HISTORY

The first attempts to record heart sounds were made by Hurthle (1893). He connected a microphone with an induction coil, thus in turn excited a frog nerve-muscle preparation which scratched a tracing on a smoked drum. Einthoven and Geluk (1894) replaced the frog preparation with a capillary electrometer and obtained a graphic picture of the first heart sound Later, Einthoven substituted the recently invented string galvanometer for the electrometer, greatly increasing the accuracy of the method

During the same period, a mechanical method for recording heart sounds was devised Frank (1904) experimented with his "segment capsule" which later became widely accepted for recording pulsations of the heart and blood vessels His method consisted of a stethoscope applied to the surface of the chest, connected by a tube to a capsule covered by a rubber membrane. Amplification of the vibrations was later obtained by using a light beam reflected by a small mirror with one edge cemented to the membrane The membrane was later made of living tissues, glass, celloidin, or gelatin With this method, important studies on heart sounds were made by Gerhartz, Garten, Ohm, and Hess.

Frank's capsule was modified in the well-known device of Wiggers and Dean, which made use of a capsule enclosed in a protective housing having a vent. The Wiggers-Dean device was used for important studies by Wiggers himself, Wolferth and Margolies, Orias and Braun-Menendez, and several other South American authors.

While these studies were proceeding, the older method of electrically recording heart sounds was further modified and perfected Trendelenburg's arrangement included a condenser microphone, an amplifier, and a Siemens oscillograph Duchosal's method was based on an electromagnetic microphone, a four-stage amplifier, and a special oscillograph permitting recording with a Boulitte electrocardiograph. Most of the French studies, like those of Lian and Racine, have been made by means of this device Lockhart's "electrostethograph" was developed by the Cambridge Instrument Co. and was based on a crystal microphone, an amplifier, and a D'Arsonval galvanometer Mannheimer's device consisted of a crystal microphone, an amplifier, and a series of channels, each [illegible]

th [illegible]

dif [illegible] and Rahm used a single crystal microphone connected to three separate amplifiers. The outputs of the latter

mal amplification for the registration of the high-frequency elements.

The use of a band-pass filter comprising a high-pass and a low-pass filter (as advocated by one of the authors) would permit scanning the vibratory spectrum in separate, adjoining bands, thus allowing a better definition of any particular vibration within each frequency band. Moreover, this arrangement would help in decreasing the "noise" level.

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Emphasis of the high-pitched vibrations can be obtained by *mechanical filters* (diaphragms of various thickness applied to the chest piece of the microphone). However, these diaphragms severely decrease the amplitude of *all* vibrations, so that increased amplification will bring out the more highly pitched vibrations only if there are no adventitious noises

In order to overcome some of these difficulties, *calibrated phonocardiography* was introduced by Mannheimer (1938). The term means that the tracing was recorded by a microphone which gave a standard type of response for a certain magnitude of vibration, and by means of "filters" which excluded certain frequencies. The final tracing recorded five separate phonocardiograms. Because of its complexity, this apparatus did not meet with widespread acceptance in spite of its sound approach to the problem

A different type of phonocardiograph was used in England by Evans and then by Leatham. The use of filters permits the exclusion of low-frequency vibrations and the relative increase of moderately high frequencies

Another method of *filtered phonocardiography* was described by Maass and Weber (1952). Several high-pass filters cut off certain frequencies from below upwards: below 35, below 70, below 140, below 250, and below 400 cps, with different slopes

A study by the authors and Richmond (1956) led to a description of select

thors found that the best way to operate the device is as follows

1 The microphone is placed over the desired area and the auscultatory phenomena are checked through electric auscultation.

2 The variable filter is activated by plugging its cable into a wall socket, its input and output cables are then connected with the phonocardiograph and the additional d-c amplifier.

3. The low- and high-pass filters are set at the desired limits

4 By manipulating the "sensitivity" knob of the d-c amplifier, the amplitude of vibrations of the filtered phonocardiogram is regulated

Subsequent to this study, a completely new apparatus was built a phonocardiograph with a double variable band-pass filter and a preamplifier[12] (Fig 3-44B)

The authors' studies have led to the following practical conclusions:

1. Tracings at the apex or midprecordium should be recorded with a band adjusted between 60 and 120 cps in order to demonstrate both the systolic and the diastolic murmurs of mitral defects.

2. Tracings over the aortic or pulmonic areas (or at Erb's point) to search for murmurs caused by aortic or pulmonic stenosis or insufficiency should be recorded with a band set between 120 and 240 cps in order to demonstrate both the systolic and the diastolic murmurs. Occasional patients with apical murmurs of lower pitch may require a band set at 30 to 60 cps while more highly pitched apical or basal murmurs may be best traced in the band between 240 and 480 cps

Comparison of the authors' tracings with those obtained by means of conventional methods (stethoscopic for the low-pitched murmurs; logarithmic with or without mechanical filters for the high-pitched) revealed such a superiority of the new method of "selective phonocardiography" that this merits use in routine phonocardiography. This superiority is particularly apparent in recording murmurs of poor magnitude (faint murmurs), high pitch (soft murmurs), or low pitch (rumbles) (Fig. 3-53).

The problem of *identifying extra sounds* occurring in diastole has a definite practical importance Recognition of a 3d or 4th sound, decision as to whether it is a significant phenomenon or not, and its differentiation from an opening snap of the mitral valve, may depend upon an exact determination of the pitch For this, a different technique has been used. both band-pass filters are placed at the same figure (20–20, 40–40, 60–60, etc). As the attenuation of the filters is not complete in the marginal fringes,[13] the vibrations nearest to the limit marked on the dial can still pass, even though they are attenuated Scanning the

[11] This filter was supplied by the Krohn-Hite Co of Boston (No 330-A).

[12] This is composed of a condenser microphone (No 21-BR-150) supplied by the Altec Co of Pasadena, of a preamplifier (No 442-A) and a power amplifier (128-A), supplied by the same company, and of a recorder and several galvanometers supplied by New Electronics Products of London, England The filter is the same as before (see footnote 11).

[13] This was done when using a No 310-AB band-pass filter The new filter No 330-A seems to have a sharper attenuation and requires bands of 20 to 40, 40 to 60, etc.

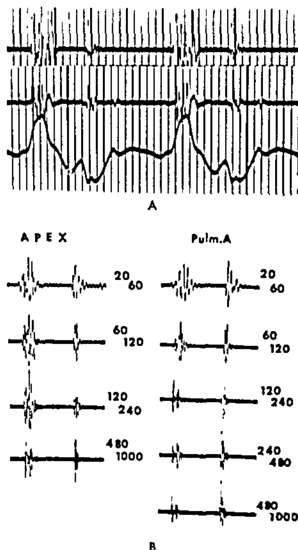


Fig. 3-44. A. Three tracings of a normal young man recorded at the apex by different methods above, logarithmic (or clinical) tracing, center, stethoscopic (or objective) tracing, below, linear tracing (low-frequency or palpatory tracing) There is a 3d sound, revealed by the stethoscopic tracing (center), which coincides with the wave of rapid filling in the linear tracing (below), the logarithmic tracing (above) does not show this sound which was inaudible. B. The heart sounds recorded through different filters of a new apparatus.

were recorded by means of cathode-ray tubes on a photographic film.

THE APPARATUS

The purpose of clinical phonocardiography is twofold (1) to record the cardiac sounds and murmurs in correlation with data revealed by auscultation (in this regard, it is an *auxiliary, bedside method*), and (2) to record correctly the same sounds and murmurs in order to study and interpret them (in this regard, it is an *independent graphic method*).

The hybrid types of phonocardiographs of the period between 1920 and 1938 gave tracings which were unsatisfactory for either of the two above-mentioned purposes. The *Sanborn phonocardiographs*, developed since 1939, tried to fulfill the two main purposes of phonocardiography by means of "logarithmic" and "stethoscopic" methods (Rappaport and Sprague, 1941, 1942) The tracings were first recorded by two different crystal microphones, each incorporating an acoustic high-pass filter for attenuating to a different degree the low-frequency vibrations (*Stetho-cardiette*). Then, they were recorded by a single dynamic microphone provided with an acoustic filter which attenuated the low-frequency vibrations (stethoscopic response); the apparatus (*Twin-beam*) also had an electronic filter which further attenuated such vibrations, thus providing for a response which was supposed to be similar to that of human hearing (logarithmic response).

The *stethoscopic response* gives a faithful reproduction of the vibrations above 100 cps as they are presented by a stethoscope to the ear[10] and with the limitations imposed by the frequency response of the galvanometer. Below 100 cps there is an attenuation of 6 db/octave, which reduces to one half the amplitude of vibrations of 50 cps having the same magnitude. In contrast, the *logarithmic response* gives a faithful reproduction above 200 cps and has an attenuation of 12 db/octave below this frequency, so that vibrations of 100 cps are reduced to one fourth of the initial magnitude (Fig 3-44A)

The stethoscopic response is useful for an analysis of the heart sounds, the logarithmic for correlation and control of clinical auscultation

In spite of the best instruments, two types of diastolic murmurs are frequently difficult to reproduce. the low-pitched apical murmur of mitral stenosis and the high-pitched basal murmur of aortic insufficiency If the vibrations are small and are not mixed with others originating in the chest or the room, amplification may reveal them better Usually, however, *there are* other vibrations, which are also amplified, so that the tracing does not become more distinct through amplification

[10] It is the authors' contention that phonocardiography should be used not only for clinical correlation, but also for a scientific analysis of the precordial vibrations For the second purpose, it would be preferable to obtain a tracing of the vibrations *as they are*, without the modification imposed by a stethoscope.

circuit which used the body as a pole. A third attempt was made by Lewis et al. (1956) who used a hollow cylinder of piezoelectric ceramic at the catheter tip for picking up the sound vibrations.

All the above-mentioned techniques require special catheters and offer several practical disadvantages in routine application. A new, simpler method is made possible by the use of filters and was described by Luisada and Liu in 1957.

The catheter placed in one of the cardiac chambers or in the large vessels contains a column of fluid which reaches from the heart to a strain gage or electromanometer. As water is a good conductor of sound vibrations, it is possible to pick up these vibrations from the end of the catheter instead of its tip. A recording is obtained by the use of three circuits of differentiation. The "differentiator" is a single section RC-type which provides differentiation (6 db/octave = stethoscopic) for signals with a frequency below 100 cps when fed to a linear amplifier. If fed to an amplifier with stethoscopic characteristics, double differentiation (12 db/octave = logarithmic) is obtained. When fed to an amplifier with special filters, triple differentiation (18 db/octave) is obtained. Signals having frequencies higher than 100 cps pass undifferentiated but are amplified. The output of the "differentiator" increases linearly with increasing frequency up to 100 cps, then gradually flattens off to give constant output. The final output is obtained through the use of low-pass and high-pass filters. Both cause the signals to decrease at a rate of 12 decibels/octave at frequencies respectively below or above those selected by the switch, while the desired frequencies pass without attenuation. Bands of 40 to 120, 40 to 250, and 40 to 500 cps are alternately used. Simultaneous pressure and sound tracings are recorded.

The pressure variations occurring in the cardiac or vascular chambers represent the summation of all the vibrations generated by the dynamic action of the heart. The pressure curve, if recorded by a transducer which is sensitive to both low and high frequencies, represents the accurate picture of all frequencies arising within the cardiovascular structures including the so-called pressure pulses, the so-called valvular sounds, and the manifestations of turbulence of the blood. Therefore, the problem of recording intracardiac sonic frequencies is solved by (1) using an adequate transducer, (2) filtering out the pressure pulses, and (3) magnifying the remaining sonic vibrations.

The strain gage transducer which is adequate for such a purpose is a *Statham* P-23 D, which reproduces accurately vibrations up to 280 cps. It is obvious that the principal cardiovascular vibrations can be adequately recorded because they are within this limit.

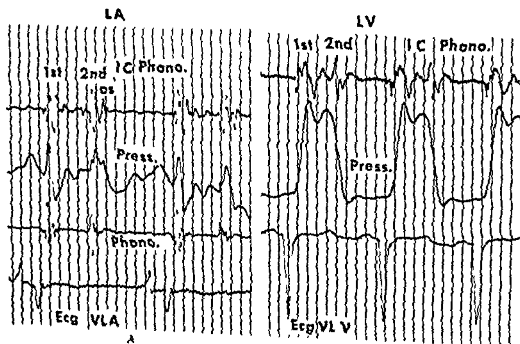


Fig. 3-45. Intracardiac phonocardiograms of dogs. A. Left atrium (LA), reading from above, intracardiac phonocardiogram, pressure tracing, external phonocardiogram, intracardiac ECG. B. Left ventricle (LV), reading from above, intracardiac phonocardiogram, pressure tracing; intracardiac ECG.

phonocardiographic picture in this way, band by band, it is possible to ascertain the frequency of a certain sound.

The frequency characteristics of a sound or murmur can also be analyzed in a different way. A special device, utilized by McKusick, transcribes vibrations of higher frequencies as vibrations of greater height. This method has been called *spectral phonocardiography* (Fig. 3-56). It utilizes a device originally developed at the Bell Laboratories by Fletcher (sound spectrograph) for the study of speech frequencies and intensities. It is based on the tape recording of a few cardiac cycles and on the extremely rapid automatic scanning of these cycles by means of a variable filter. The final tracing reproduces vibrations of different frequencies on a graph, the ordinate of which represents frequencies while the abscissa represents time.

Recording: Film Speed. The recording of phonocardiograms is best accomplished through *photographic* methods. *Direct writers* using the "hot" pen device can be employed, at best, for timing other signals. The Schwarzer apparatus gives a more accurate tracing. However, even this tends to reproduce groups of high-frequency vibrations as units and to approximate somewhat that principle which has been used by Rushmer for the *sonvelogram*. In a sonvelogram, the "shape" of a murmur is outlined without reproduction of the individual vibrations which cause that "shape." An apparatus using the "jet" principle (Elema) seems to give an accurate transcription.

Accurate reproduction of the individual vibrations of a sound or murmur requires high film speed. This should be between 75 and 150 mm/sec. Speeds lower than 75 *mm/sec* may be useful for giving a visual impression of the "shape" of a murmur but not for an accurate study.

THE PROBLEM OF CALIBRATION

The problem of "calibration" of heart sounds and murmurs has been a stumbling block which prevented clinical development of phonocardiography for several decades. While a clinical tracing may be studied without reference to the absolute magnitude of sounds or murmurs, accurate determination of the latter is of interest and adds to the accuracy of the method.

A sound calibrator, devised by Olson and Maass and modified by Dunn and Rahm, was based on the comparison of two juxtaposed cathode-ray beams. The system was used for calibration of microphones and not for direct calibration of the vibrations recorded from patients.

Another type of calibrator was introduced by the Sanborn Company. Pressing a button gives an electric signal of 60 vibrations/sec and is recorded with a magnitude which is comparable to that of a sound of 90 db above threshold hearing taking place within the microphone.

The two above-described systems have a certain value because they permit the use of a standard degree of amplification. When two tracings are recorded with the same magnitude of calibrating signal, instrumental differences can be excluded. On the other hand, several variables can still modify the magnitude of the cardiac vibrations recorded by the microphone.

For these reasons, a *clinical calibrator* was developed (Luisada and Gamna, 1954). This consists of a small plastic box containing a 6-volt vibrator giving a sound signal of 100 cps.

If the vibrations of the sound signal could be made to originate within the mediastinum, their transmission would be modified by the same causes which modify the transmission of the heart sounds. All efforts in that direction having failed, the sound calibrator was applied over the chest wall and the best location was empirically established. With the calibrator over the left pectoral muscle, the vibrations are transmitted partly through the chest wall and partly through the lungs, as demonstrated by both animal experiments and observations on man.

Various causes of error in phonocardiography, like changes of the electrical characteristics of the system, modification of tension of the microphone against the skin, variable thickness of the chest wall, or improper application of the microphone, are automatically revealed by changes in magnitude of the vibrations of the sound calibrator, so that the latter may be effectively used as a standard. Changes in resonance of the chest wall due to pleural effusion are also revealed by the calibrator, even though no absolute proportionality can be found between the changes of magnitude of the heart sounds and those of the vibrations of the signal. Less accurate proportionality is found in regard to extreme inspiratory or expiratory apnea, due to the interaction of multiple factors.

INTRACARDIAC PHONOCARDIOGRAPHY

Intracardiac phonocardiography was first attempted by Soulié (1954) with a tiny piezoelectric microphone applied to the tip of a catheter. A second attempt was made by Yamakawa and coworkers. They used a small metal stick attached to the tip of a catheter and placed in an electric

circuit which used *the body as a pole.* A third attempt was made by Lewis et al. (1956) who used a hollow cylinder of piezoelectric ceramic at the catheter tip for picking up the sound vibrations.

All the above-mentioned techniques require special catheters and offer several practical disadvantages *in routine* application A new, simpler method is made possible by the use of filters and was described by Luisada and Liu in 1957.

The catheter placed in one of the cardiac chambers or in the large vessels contains a column of *fluid which reaches from* the heart to a strain gage or electromanometer As water is a good conductor of sound vibrations, it is possible to pick up these vibrations from the end of the catheter instead of its tip A recording is obtained by the use of three circuits of differentiation The "differentiator" is a single section RC-type which *provides differentiation* (6 db/octave = stethoscopic) for signals with a frequency below 100 cps when fed to a linear amplifier. If fed to an amplifier with stethoscopic characteristics, double differentiation *(12 db/octave = logarithmic) is obtained* When fed to an amplifier with *special* filters, triple differentiation (18 db/octave) is obtained. Signals having frequencies *higher than* 100 *cps pass* undifferentiated but are amplified The output of the "differentiator" *increases* linearly with increasing frequency up to 100 cps, then gradually flattens off to give constant output. The final output is obtained through the use of low-pass and high-pass filters. Both cause the signals to decrease at a rate of 12 decibels/octave at frequencies *respectively below or above those* selected by the switch, while the desired frequencies pass without attenuation. Bands of 40 to *120*, 40 to 250, and 40 to 500 cps are alternately used Simultan [illegible]

or [illegible]

all the vibrations *generated by the dynamic action* of the heart. The pressure curve, if recorded by a transducer which is sensitive to both low and high frequencies, represents the accurate picture of all frequencies arising within the cardiovascular structures including the so-called pressure pulses, the so-called valvular sounds, and the manifestations of turbulence of the blood. Therefore, the problem of recording intracardiac sonic frequencies is solved by (*1*) using an adequate transducer, (2) filtering out the pressure pulses, and (3) magnifying *the remaining sonic vibrations*

The strain gage transducer which is adequate for such a purpose is a *Statham P-23 D*, which reproduces accurately vibrations up to 280 cps. It is obvious that the principal cardiovascular vibrations can be adequately recorded because they are within this limit.

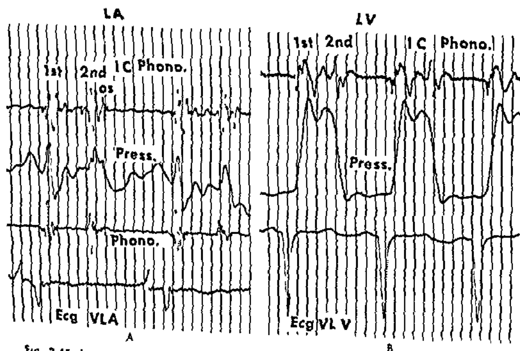


Fig 3-45. *Intracardiac* phonocardiograms of dogs A Left atrium (LA), reading from above: intracardiac phonocardiogram, *pressure tracing, external* phonocardiogram, intracardiac ECG. B Left ventricle (LV), *reading* from above intracardiac phonocardiogram; pressure tracing; intracardiac ECG

phonocardiographic picture in this way, band by band, it is possible to ascertain the frequency of a certain sound

The frequency characteristics of a sound or murmur can also be analyzed in a different way. A special device, utilized by McKusick, transcribes vibrations of higher frequencies as vibrations of greater height. This method has been called *spectral phonocardiography* (Fig. 3-56). It utilizes a device originally developed at the Bell Laboratories by Fletcher (sound spectrograph) for the study of speech frequencies and intensities It is based on the tape recording of a few cardiac cycles and on the extremely rapid automatic scanning of these cycles by means of a variable filter. The final tracing reproduces vibrations of different frequencies on a graph, the ordinate of which represents frequencies while the abscissa represents time.

Recording: Film Speed. The recording of phonocardiograms is best accomplished through *photographic* methods *Direct writers* using the "hot" pen device can be employed, at best, for timing other signals The Schwarzer apparatus gives a more accurate tracing However, even this tends to reproduce groups of high-frequency vibrations as units and to approximate somewhat that principle which has been used by Rushmer for the *sonvelogram* In a sonvelogram, the "shape" of a murmur is outlined without reproduction of the individual vibrations which cause that "shape." An apparatus using the "jet" principle (Elema) seems to give an accurate transcription

Accurate reproduction of the individual vibrations of a sound or murmur requires high film speed This should be between 75 and 150 mm/sec Speeds lower than 75 mm/sec may be useful for giving a visual impression of the "shape" of a murmur but not for an accurate study

THE PROBLEM OF CALIBRATION

The problem of "calibration" of heart sounds and murmurs has been a stumbling block which prevented clinical development of phonocardiography for several decades While a clinical tracing may be studied without reference to the absolute magnitude of sounds or murmurs, accurate determination of the latter is of interest and adds to the accuracy of the method.

A sound calibrator, devised by Olson and Maass and modified by Dunn and Rahm, was based on the comparison of two juxtaposed cathode-ray beams. The system was used for calibration of microphones and not for direct calibration of the vibrations recorded from patients.

Another type of calibrator was introduced by the Sanborn Company. Pressing a button gives an electric signal of 60 vibrations/sec and is recorded with a magnitude which is comparable to that of a sound of 90 db above threshold hearing taking place within the microphone

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the low-pitched vibrations is extremely poor (unless they are of great intensity) and gradually increases for the higher frequencies

The normal heart is the source of vibrations with a normal frequency between 5 and 800 per second while cardiac murmurs may occasionally attain 1,000 vibrations per second and more. It should be kept in mind that, because of different intensity of the vibrations, 90 per cent of them are *below* the limits of audibility, and could be named *infrasounds*, while a good percentage of the others is in the borderline range, so that they are heard only by particularly well-trained observers, or are too weak to be heard (*subliminal sounds*)

The scale of sensitivity of the ear with regard to frequency increases very rapidly, on a logarithmic scale It is only at the frequency of 1,000 cps that a given increase of intensity results in the same increase in loudness In bands of lower frequency, much larger increases in intensity are necessary in order to cause the same result.

In the presence of certain large or high-pitched sounds, the ear may be unable to detect soft or lower pitched sounds which follow immediately This phenomenon is called "masking."

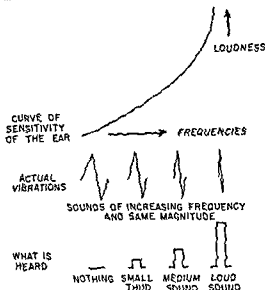


Fig. 3-47. One of the physiological failures of the auditory system higher-pitched sounds are heard as louder sounds (From Luisada and Aravanis. M. Clin. North America, 1957. Courtesy of W. B. Saunders Co.)

NORMAL HEART SOUNDS

The phonocardiogram of a normal subject may record up to *four principal heart sounds* and occasionally more. The two louder sounds are called the 1st and 2d sounds, the others, the 3d and 4th sounds. The 3d and 4th *sounds take place* during diastole and are connected *with the phases* of ventricular filling (rapid *passive filling* = 3d sound; rapid active filling caused by *atrial* contraction = 4th sound) *Therefore, they* have been called *diastolic sounds* The more commonly heard and louder 1st and 2d sounds are strictly connected with ventricular systole (*beginning of systole* = 1st sound, end of *systole = 2d sound*) It has been suggested that they be *called systolic sounds* (Luisada)

The *first sound complex* is caused by a complex musculovalvular *mechanism*, and it is impossible to attribute *any separate vibration* to a special factor (Part 2, Chap 10) However, two groups of taller vibrations were recorded by phonocardiographs of the older type. The coincidence of the first group with the beginning of ventricular systole, and of the second with the rise of the carotid pulse was accepted as evidence that the former was due to vibrations of the heart coinciding with AV-valve closure while the second was due to vibrations coinciding with semilunar-valve opening (Luisada, Mendoza, and Alimurung) An alternate interpretation, not supported by convincing evidence (Leatham), attributed the first group to mitral closing, the second to tricuspid closing.

More recent phonocardiographic documents obtained by means of a Peiker microphone and a cathode-ray oscilloscope have revealed *four groups* of vibrations within the first sound complex (Luisada and Liu) Intracardiac pressure tracings have revealed that each of them coincides with a valvular motion in the following order,—mitral closure—tricuspid closure (first group of two),—pulmonic opening—aortic opening (second group of two) (Fig. 3-48).

Physiological splitting of the 1st sound in normal hearts is caused by greater separation of the two principal groups, a fact which becomes particularly apparent if one records the sounds at the mid-precordium (so-called *tricuspid area*) in the band from 200 to 400 cps, *as done* by Leatham

The 2d sound is usually simpler and shorter. *Its principal* group of vibrations is due to the

Following in vitro experiments where sounds applied to water in an open container were recorded from the strain gage while only minimal changes in pressure took place, several controls were made in animals. The following data were observed (Fig 3-45):

1. Sounds and murmurs are easily recorded from inside the heart. A minimal delay of the intracardiac heart sounds (0.01 to 0.01 sec) seems to occur in relation to those recorded over the chest.

2. The magnitude of the two principal heart sounds decreases in the following order: left ventricle, right ventricle, ascending aorta and pulmonary artery, left atrium, right atrium.

3. Diastolic sounds and systolic or diastolic murmurs are recorded.

4. Respiration does not interfere with intracardiac phonocardiography.

5. The thin polyethylene catheter used in left heart catheterization has a slightly damping effect which, however, does not prevent obtaining a good tracing.

The heart sounds from inside the heart can be checked before recording by using either an oscilloscope (*visual*) or an audiophone (*auditory*).

With this technique, the only new device added to the instrumentation is a specially built phonocardiographic circuit, connected by a short cable to that of the strain gage. It is self-evident that, as in routine phonocardiography, a correct tracing can be obtained only by using photographic recording. Interesting data have been obtained in patients with defects of the mitral valve (Fig 3-46).

THE LAWS OF AUSCULTATION

It is well known that the auditory system of man contains inherent properties and limitations. Knowledge of the latter explains some of the pitfalls of auscultation and certain unavoidable discrepancies between clinical impressions and objective data. These limitations may be summarized as follows:

Pure tones of different pitch and the same intensity are heard as tones of different intensity.

The ear detects more easily changes of pitch than changes of intensity (except in lower frequency ranges where changes of pitch may not be detected at all). As a result, a more *highly pitched tone* of the same intensity is heard as a *louder* tone (Fig. 3-47).

The ear cannot perceive vibrations having a *frequency* below 20/sec or an *intensity* below 2/1,000 dyne/cm². In addition, sensitivity to

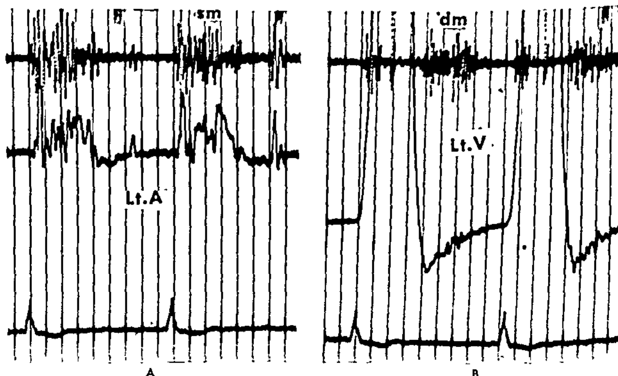


Fig. 3-46. Intracardiac phonocardiograms in a case of double mitral defect. A Left atrium (Lt A.) larger systolic murmur (sm). B Left ventricle (Lt V). larger diastolic murmur (dm); reading from above: intracardiac phonocardiogram; pressure tracing, ECG.

TABLE 3-5. AVERAGE DURATION OF THE HEART SOUNDS, THEIR PHASES, AND THEIR INTERVALS, IN SECONDS (STETHOSCOPIC TRACINGS)

Ages, years	First sound at apex				Second sound at base				Third sound	Sound	
	Total duration	First phase	Second phase	Third phase	Total duration	First phase	Second phase	Third phase		4-1	2-3
Below 4	0.070	—	0.040	0.030	0.060	—	0.020	0.040	—	—	—
4-10	0.120	—	0.040	0.080	0.110	0.019	0.055	0.050	0.050	0.060	0.12
11-20	0.147	0.018	0.069	0.071	0.120	0.029	0.034	0.056	0.050	0.060	0.14
21-40	0.146	0.020	0.063	0.078	0.114	0.018	0.043	0.055	0.061	0.064	0.16
41-60	0.145	0.020	0.057	0.080	0.098	0.013	0.040	0.053	0.057	0.061	0.18
Above 60	0.141	0.024	0.050	0.080	0.085	0.010	0.038	0.044	—	0.050	—
Over-all avg above age 10	0.146	0.020 (46%)	0.060	0.077	0.104	0.015 (38%)	0.039	0.052	0.059 (50%)	0.058 (78%)	0.15 (50%)

SOURCE: From Luisada, Heart Beat, Hoeber, 1953.

the beginning and the end of these two phases, *especially the last. Therefore, it was suggested* that the sound be divided into only three phases, (1) initial, slow vibrations; (2) central, large vibrations, (3) final, slow vibrations.

The *total average duration of the 1st sound* at the apex with the *stethoscopic microphone* in patients aged more than 10 years is 0.146 sec. The maximum total duration of the first sound complex at the apex is 0.16 sec between 11 and 20 years and 0.22 sec in older subjects. The average duration of the second (or central) phase of the 1st sound at the apex is 0.06 sec for patients aged more than 10 years. The maximum duration of the second (central) phase is 0.12 sec in the group from 11 to 20 years and 0.10 sec in older groups of subjects. Figures greater than these reveal the existence of a systolic murmur.

Second Sound Complex. The 2d sound is frequently longer in graphic tracings than it seems at auscultation. It is caused by the closure of the semilunar valves of the aorta and pulmonary artery. The subsequent opening of the AV valves may add small vibrations. Four parts or components can be distinguished within the complex. However, following practical considerations, it has been suggested that it be divided into three phases only, the second, or central, phase, composed of large vibrations, is the most important for clinical purposes.

The *total average duration* of the 2d sound at the base with a "stethoscopic" microphone is 0.12 sec in the age group 11 to 20 years. The average duration of the central (second) phase of this sound is 0.034 sec in the age group 11 to 20 years. The maximum duration is 0.16 sec for the

TABLE 3-6. EXTREME VARIATIONS OF THE HEART SOUNDS AND THEIR MAIN PHASES, IN SECONDS (STETHOSCOPIC TRACINGS)

Ages, years	First sound at apex				Second sound in aortic area			
	Maximum		Minimum		Maximum		Minimum	
	Total duration	Second phase	Total duration	Second phase	Total duration	Second phase	Total duration	Second phase
11-20	0.16	0.12	0.12	0.04	0.12	0.04	0.08	0.03
21-40	0.22	0.10	0.09	0.02	0.16	0.10	0.08	0.03
41-60	0.22	0.10	0.07	0.03	0.14	0.06	0.06	0.02

SOURCE: From Luisada, Heart Beat, Hoeber, 1953.

closure of the semilunar valves, and a study of these vibrations can give information about the function of the aortic and pulmonic valves. Usually, the aortic valve closes first, the pulmonic later. An asynchronism of 0.02 to 0.03 sec between aortic and pulmonic closure is revealed by recording the tracing in the 2d or 3d left interspace in the band from 200 to 400 cps (Leatham). The first, larger vibration is aortic; the second, smaller vibration, pulmonic.

Following these vibrations, small notches, due to the opening of the AV valves, can be observed. If there are two of them, the first indicates tricuspid, the second, mitral opening (Part 2, Chap. 10). Mitral opening frequently becomes loud, snapping, and delayed in mitral stenosis (opening snap of the mitral valve) giving the auditory impression of a reduplicated 2d sound.

The *3d sound* and the *4th sound* usually consist of one or two small, low-pitched vibrations which are recorded best in the band from 30 to 60 cps. The 3d sound may be audible in children, young adults, or persons with a thin, flat chest. Increased loudness of either the 3d or the 4th sound is the most common cause of the triple rhythms (so-called gallop rhythms).

The duration of the 1st and 2d sounds, as well as of their phases, and the intervals separating these sounds from each other have been repeatedly investigated, so that tracings of patients under observation can be evaluated with the help of average and extreme figures (Tables 3-5 to 3-8).

DURATION OF HEART SOUNDS

According to the system of recording, the heart sounds may be of different durations. This is because certain frequencies contained in the sounds may be excluded by the filtering system of the phonocardiograph.

First Sound Complex. The division of the 1st sound into five parts has important theoretical implications; however, a simplified method has practical advantages (Luisada et al., 1949). The main portion of the sound is made up of large, irregular vibrations (Parts 2, 3, 4) while the beginning (Part 1) and the end (Part 5) are made up of slower vibrations. It is not always easy to locate

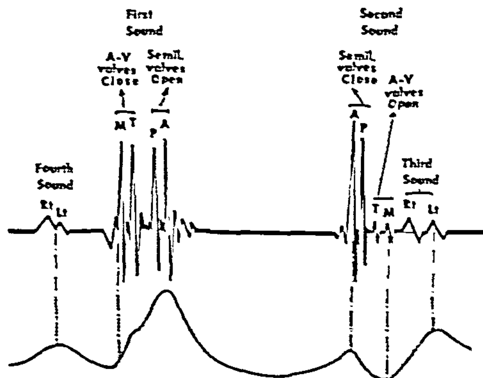


Fig. 3-48. Scheme of a phonocardiogram recorded with a high-sensitivity microphone and a cathode-ray oscillograph (filters at 60 to 110 cps). There are four vibrations within the 1st sound and two within the 2d. The splitting of the 3d and 4th sounds and that of the opening sound of the AV valves can be seen in conditions of cardiovascular overactivity or in pathological conditions. The lower tracing is an "apex cardiogram" (ultra low-frequency tracing of the apex).

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	Total duration	*First phase*	*Second phase*	*Third phase*	*Total duration*	*First phase*	*Second phase*	*Third phase*		4-1	2-3
Below 4	0 070	—	0 040	0 030	0.060	—	0 020	0 040	—	—	—
4-10	0 120	—	0 040	0 080	0 110	0 010	0 055	0 050	0 050	0 060	0 12
11-20	0 147	0 016	0 069	0 071	0 120	0 020	0 034	0 056	0 050	0 060	0 14
21-40	0 146	0 020	0 063	0 078	0 114	0 018	0 043	0 055	0 061	0 064	0 16
41-60	0 149	0 020	0 057	0 080	0 098	0 013	0 040	0.053	0 057	0 061	0 19
Above 60	0 141	0 024	0 050	0 080	0 085	0 010	0 038	0 044	—	0 050	—
Over-all avg above age 10	0 146	0 020 (46%)	0 060	0 077	0 104	0 015 (38%)	0 039	0 052	0.059 (50%)	0 058 (78%)	0 15 (50%)

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	Total duration	*Second phase*	*Total duration*	*Second phase*	*Total duration*	*Second phase*	*Total duration*	*Second phase*
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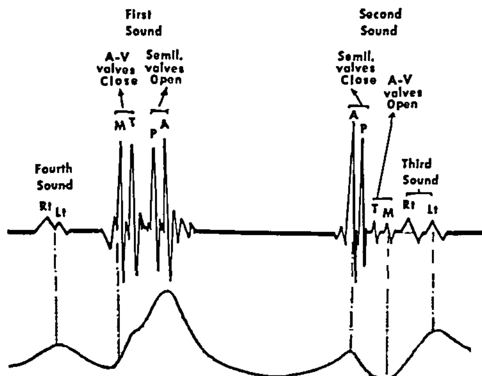


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occurrence of diastolic sounds in tracings of normal subjects in whom auscultation revealed only a two-sound rhythm (a diastolic sound may not be audible because it is low-pitched, weak, or too near the first sound). Therefore, the problem of whether a triple rhythm is physiological or pathological was studied in our laboratory on the basis of graphic data (Luisada and Roitman, 1949, Friedland and Jacono, 1959).

Triple Rhythm Caused by Addition of a Diastolic Sound (Diastolic Gallop). Three *types have been recognized.*

VENTRICULAR TYPE This is caused by increased loudness or high pitch of the 3d sound, which takes place in early diastole at the time of rapid ventricular filling. It is not unusual in normal subjects under the age of 25, but it *is more readily* produced in the presence of tachycardia. Whenever it is found in subjects over 25 to 30 years, it represents evidence of ventricular strain and indicates a less favorable prognosis. A special type of diastolic sound can be observed in *constrictive pericarditis,* where the extra sound occurs early in diastole (about 0 10 sec after the 2d sound) and is loud and high-pitched

ATRIAL TYPE This is caused by increased loudness or high pitch of the 4th sound, which takes place in presystole, at the time of the atrial contraction It is not uncommon, even in normal subjects, over the age of 25 to 30 years. Its audibility is favored by prolongation of the AV conduction It is more common in hearts affected by coronary artery disease or hypertension, concomitant with ventricular strain and increased left atrial pressure It represents the result of some degree of atrial engorgement and indicates a less favorable prognosis

SUMMATION TYPE This is caused by the summation of the 3d and 4th sounds in mid-diastole as a result of severe tachycardia, the resulting sound is complex and prolonged.

In patients with a diastolic type of triple rhythm, slowing of the heart or decrease of the ventricular load may cause disappearance of the extra sound

Quadruple Rhythm. Whenever both the 3d and 4th sounds are loud and high-pitched, a *quadruple rhythm* takes place This requires a relatively slow heart beat and a condition of ventricular strain with some engorgement of one or both the atria

Triple Rhythm Caused by Addition of a Sound in Systole. Several types have been described.

1. There may be addition of a sound of medium pitch in early systole, over either the aortic or the pulmonic areas.[14] It is due to vibrations *arising in the vascular walls* because of increased pressure or pathological change in one of the larger arteries

2 There may be a loud and rapid vibration near midsystole, usually heard and recorded best at the apex *(systolic click or snap).* It has been attributed to traction of *pleuropericardial* or *diaphragmopericardial adhesions.*

3 A third type is encountered in cases of congenital heart disease with an overriding aorta, especially in the *tetralogy of Fallot* The extra sound is in early systole and is recorded best over the midprecordium. A tentative explanation of this sound is that it is due to a vibration of the free, overriding wall of the aorta.

Triple Rhythm Caused by Increased Loudness of the Opening Sound of the Mitral Valve. An audible opening sound of the mitral valve may be found, though rarely, in normal subjects. Patients with mitral stenosis, on the other hand, frequently present a loud *snap,* coinciding with and caused by the opening of *the stenotic* mitral valve The sound is high-pitched and may be recorded over the entire precordium, even though it is usually recorded best over the 3d and 4th left interspaces.

SPLITTING OF THE SECOND SOUND

In normal subjects, the pulmonic component of the 2d sound takes place slightly after the aortic component (0 02 to 0 03 sec).

Splitting of the 2d sound is caused by asynchronism of closure of the aortic and pulmonic valves As the pulmonic component is fainter and has a poorer transmission, a split 2d sound usually is *heard* only over the 2d left interspace, which is near the anatomical projection of both the aortic and pulmonic valves. On the other hand, *graphic tracings* at times show a *split* 2d sound *also* over the 2d right interspace.

[14] This *sound is* a typical phonocardiographic finding but may become audible if of great magnitude (Luisada, 1948). It *should* not be confused with the opening click of the aortic or pulmonic valves, which occurs *earlier* (at the end of the 1st sound) and which will be described below.

TABLE 3-7. AVERAGE LENGTH OF HEART SOUNDS IN 139 CHILDREN, IN SECONDS (STETHOSCOPIC TRACINGS)

Age, years	*No of cases*	*First sound*				*Second sound*				*Sound*			*Area*
		Total duration	*First phase*	*Second phase*	*Third phase*	*Total duration*	*First phase*	*Second phase*	*Third phase*	3	4-1	2-3	
2–3	10	0 108	0 019	0 044	0 035	0.070	0 011	0 030	0 030	0 040	0 054	0 100	apex
		0 109	0 022	0 055	0 032	0.076	0.015	0 029	0 032	—	0 088	—	base
3–4	10	0 108	0 020	0 054	0.039	0 063	0 016	0 031	0 024	0 051	—	0 102	apex
		0 103	0 022	0 052	0 035	0 063	0 010	0 027	0 036	—	—	—	base
4–5	10	0 105	0 016	0 050	0 038	0 073	0 016	0 022	0 038	0 049	0 014	0 101	apex
		0 116	0 021	0 053	0 039	0 083	0.012	0 032	0 044	—	0.024	—	base
5–6	16	0 120	0 017	0 054	0 050	0 105	0 018	0 034	0.050	0 056	0 051	0 096	apex
		0 133	0 028	0 056	0 049	0 124	0 028	0 032	0 064	—	0 076	—	base
6–7	20	0 126	0 023	0 053	0 050	0 111	0 028	0 039	0 048	0 064	0 051	0 105	apex
		0 120	0 027	0 057	0 036	0 118	0 024	0 042	0 052	0.075	0 092	0 125	base
7–8	10	0 118	0 024	0 056	0 043	0 092	0 019	0 038	0 037	0 058	0 064	0 115	apex
		0 115	0 023	0 059	0 043	0 093	0 010	0 036	0 050	0 100	0 066	0 112	base
8–9	11	0 089	0 018	0 042	0 030	0 068	0 018	0 025	0 029	0 056	0 040	0 105	apex
		0 093	0 021	0 034	0 032	0.072	0 012	0 034	0 038	—	0 080	—	base
9–10	11	0 124	0 025	0 058	0 041	0 093	0 020	0 030	0 045	0 072	0 046	0 097	apex
		0 131	0 030	0 055	0 046	0 081	0 012	0 038	0 040	0 120	—	0 100	base
10–11	11	0 118	0 022	0 059	0 038	0 089	0 019	0 034	0 044	0 071	0 057	0.130	apex
		0 133	0 033	0 056	0 045	0 101	0 020	0 037	0 050	—	0 106	—	base
11–12	10	0 112	0 030	0 057	0 031	0 088	0 018	0 032	0 046	0 056	0 055	0 114	apex
		0 102	0 020	0 055	0 034	0 076	0 012	0 033	0 039	—	—	—	base
12–13	10	0 121	0 025	0 056	0 040	0 096	0 018	0 030	0 054	0 050	0 054	0 120	apex
		0 113	0 024	0 060	0 042	0 099	0 019	0 032	0 066	—	0 077	—	base
13–14	10	0 133	0 026	0 065	0 044	0 098	0 023	0 035	0 051	0 053	0.050	0 106	apex
		0 139	0 024	0 066	0 054	0 105	0 022	0 039	0 057	—	0 024	—	base

SOURCE From Aravanis and Cardi, 1956

total sound and 0.10 for the second (central) phase, in the age group 21 to 40 years

Special tables for values in normal children have been prepared by Aravanis and Cardi, and for the aged by Aravanis and Harris.

INTERVALS BETWEEN HEART SOUNDS

The normal heart sounds are separated by intervals which do not exceed certain limits and which may help in the recognition of extra sounds

The *interval between the beginning of the 2d sound and the beginning of the 1st* may be as short as 0 05 sec at the base in patients between 41 and 60 years of age and as long as 0 072 sec at the apex in persons between 21 and 40 (unless there is AV block) The over-all average is 0 058 sec upon all areas of the precordium Children of various ages have different data.

The *interval between the 1st and 2d sounds* varies according to the various lengths of ventricular systole The duration of electrical systole varies according to the heart rate, the mechanical systole is slightly shorter than the electrical and can be reckoned as the length of electrical systole minus one-half of the duration of QRS, in other words, mechanical systole is about 0 04 to 0 05 sec shorter than electrical systole.

The *interval between the 3d and 4th sounds* varies considerably depending on the duration of ventricular diastole If diastole is short, as in tachycardia, this interval may disappear altogether and there may be a "summation" type of triple rhythm

TABLE 3-8 AVERAGE LENGTH OF HEART SOUNDS IN 100 OLD PERSONS, IN SECONDS (STETHOSCOPIC TRACINGS)

Age, years	*First sound*		*Second sound*	
	Total duration	*Central phase*	*Total duration*	*Central phase*
60–69	0 182	0 052	0 110	0 042
70–79	0 174	0 051	0 109	0 041
80–89	0 168	0.055	0 102	0 039
90–108	0 158	0 054	0 094	0 039

SOURCE: From Aravanis and Harris, 1958.

TRIPLE AND QUADRUPLE RHYTHMS

The term "triple rhythm" has been suggested to indicate the presence of a cadence of heart sounds which is caused by the addition of one extra sound to the two more commonly heard sounds.

Phonocardiography has revealed the frequent

ventricle. This leads to formation of *three groups of vibrations* within the 1st sound complex; the central phase is the loudest because it is due to summation of vibrations arising in both ventricles.

The dynamics of valvular opening and closing become more complex whenever bundle branch block is complicated by intraventricular block, hypertension, or a shunt. Then, if increased flow or increased pressure adds its effect to that of the bundle branch block, or if there is intraventricular block of the same side, the dissociation between the two ventricles may become so marked that actual splitting of the 1st sound may occur

MURMURS

General Characteristics. The frequency characteristics of cardiac murmurs have been the object of several investigations Cabot and Dodge and Williams and Dodge, listening through electric filters, recognized that, while low-pitched murmurs had vibrations in the range of from 120 to 400 cps, nine out of eleven cases had vibrations below 120 cps. The high-pitched murmurs had vibrations between 240 and 400 cps, with some reaching up to 660 and occasionally 1,000 cps In each individual case, a large percentage of the total energy was in a relatively narrow band.

With a similar method of filtering and listening to cardiac murmurs, Butterworth et al found that the frequencies of most systolic murmurs were between 80 and 120 cps, those of mitral diastolic murmurs were between 40 and 100 cps, and those of the aortic diastolic murmurs were between 100 and 200 cps

Luisada et al (1956) made a graphic analysis of murmurs by means of a variable band-pass filter with similar results Most vibrations of clinical importance were found in the bands of low and medium frequency Even in patients having high-pitched vibrations (600 cps or more), there may be such a predominance of energy in the vibrations below 200 cps that the best tracing is still that recorded between 120 and 240 cps In this study, frequencies above 400 cps were recorded only with extreme amplification, and those above 600 cps were minimal and difficult to register

Cardiac murmurs are transcribed as complex groups of vibrations It is easy to decide whether the most significant groups of vibrations are *low-pitched* (more separated) or *high-pitched* (near and packed together), whether they correspond to a *rumble* (sparse and irregular vibrations), and whether the murmur is *musical* (regular vibrations).

The relationship of these vibrations to the heart sounds indicates whether the murmur is *systolic*, *early-diastolic*, or *presystolic* [18]

The graphic disposition of the vibrations has led to recognition of several types of murmurs according to their "shape." In many cases, the "graphic shape" of a murmur, which can only be guessed by auscultation, has a diagnostic significance.

While this "shape" can be easily observed on an average tracing, a special device gives an automatic contour of the murmur (sonvelography, Rushmer et al). The sonvelograph transforms the heart sounds and murmurs into "envelopes" proportional to the logarithm of sound intensity.

Systolic Murmurs. A systolic murmur is revealed by the phonocardiogram as a series of vibrations of different pitches Only in certain cases does the tracing present regular vibrations of the same frequency, then, auscultation reveals a "musical," "sea-gull cry," or "cooing dove" type of murmur

The following types of systolic apical murmurs can be observed:

1. *Prolongation of the second phase of the 1st sound* in spite of the fact that the over-all length of the sound is still within average or maximum limits

2 *Prolongation of the total duration of the 1st sound,* which lasts beyond the peak of the C wave of the jugular tracing or the peak of the main wave of the carotid tracing The murmur is more prolonged

3 *Murmur in decrescendo* (Fig. 3-49B). This has larger vibrations at first, smaller vibrations later. It usually ends long before the 2d sound. It is composed of vibrations of dif-[illegible]

[illegible] recorded best at the apex.

4 *Low-grade, all-systolic murmur,* usually made up of high-pitched vibrations It lasts

[18] The term "middiastolic murmur" is frequently inaccurate if used in descriptions of graphic tracings of diastolic murmurs A murmur is a prolonged series of vibrations Only in rare cases is diastole so long and the murmur so placed that such a term is justified.

Physiological splitting is frequent in children and occasionally found in adults, with periodic occurrence due to respiration: the smaller pulmonic component is periodically delayed in inspiration.

In cases of *mitral stenosis*, splitting of the 2d sound is frequent. The high pressure of the pulmonary circulation leads to longer duration of right ventricular systole, so that the loud pulmonic falls *after* the aortic component. In *chronic cor pulmonale*, as well as in *primary pulmonary hypertension*, a similar mechanism may cause splitting of the 2d sound In these cases, splitting of the 2d sound may even be recorded at the apex.

In *pulmonic stenosis*, the pulmonic component is small and delayed Should one set the end of systole at the time of the normal (aortic) 2d sound, then the pulmonic component would seem to fall in early diastole. In *aortic stenosis*, the aortic component may be small and delayed. In *complete bundle branch block*, splitting of the 2d sound is common In *right bundle branch block*, delayed activation causes delayed contraction of the right ventricle, the pulmonic component of the 2d sound falls from 0 04 to 0 08 sec after the aortic component. Pulmonary hypertension would exaggerate the interval between the two components. In *left bundle branch block*, delayed activation causes delayed contraction of the left ventricle, the aortic component of the 2d sound falls from 0 02 to 0 04 sec after the pulmonic component Systemic hypertension would increase the delay, pulmonic hypertension would decrease the delay or even mask it. This splitting, which is less constant than in right bundle branch block, has been called "paradoxical splitting" by Leatham

SPLITTING OF THE FIRST SOUND

Apparent splitting of the 1st sound may occur whenever its components of higher frequency are widely separated This may be physiologically noted if the tracing is recorded over *the midprecordium (3d left interspace)* and is due to separation of the mitral-tricuspid closing vibrations (1st group) from the aortic-pulmonic opening vibrations (2d group) (Part 2, Chap 10) This splitting may occasionally become audible and may be considered abnormal only if the two groups of vibrations are separated by more than 0.04 to 0 05 sec

An apparent splitting is recorded beyond the usual area (and is also heard) when there is *an abnormality in either the aortic or the pulmonic valve*. Then, the usually moderate vibrations which accompany the opening of the valve become extremely large (*opening click of the aortic or pulmonic valve*, described by Gallavardin, Lian and coworkers, and others, reemphasized by Leatham[15]). This click can be recorded over the aortic area in patients with fibrosis or calcification of the aortic valve, with moderate stenosis; occasionally, in patients with aortitis or hypertension It can be recorded over the pulmonic area in patients who have moderate pulmonic stenosis or pulmonary hypertension with a dilated pulmonary artery. Such a group of vibrations, which occurs at the end of the central phase of the 1st sound (phase of the large, medium- or high-pitched vibrations) should be differentiated from the lower-pitched vibrations which occur normally at the end *of the 1st sound*, which become larger in patients with aortitis, hypertension, or dilatation of the aorta or pulmonary artery, and which are recorded best with a stethoscopic system (see above)

Splitting of the 1st sound as a result of ventricular asynchronism due to bundle branch block has been repeatedly described. Luisada and Contro found that the 1st sound was *prolonged* in all cases of bundle branch block and had *a low amplitude*. In none of the cases was there evidence of a splitting of the 1st sound if the tracing was recorded with the stethoscopic system

In pure bundle branch block, a delay of 0 04 sec is too short to cause dissociation of a sound complex having a central phase of 0 06 to 0 08 sec and two groups of vibrations separated by an interval of 0 04 sec. If the delay between the contractions of the ventricles reaches 0 05 sec, this time interval becomes equivalent to the duration of the isometric tension period Then, closure of the AV valves of the delayed ventricle takes place during the *opening of the semilunar valves of the normal*

[15] Leatham called this sound "ejection sound" The authors believe that this term is inaccurate because the vibrations coincide with the opening of the valve and precede the most important part of the phase of distention of the vessel Instead of being an entirely new phenomenon, this click represents the intensification of a group of vibrations which occur under normal conditions.

ventricle. This leads to formation of *three groups of vibrations* within the 1st sound complex, the central phase is the loudest because it is due to summation of vibrations arising in both ventricles

The dynamics of valvular opening and closing become more complex whenever bundle branch block is complicated by intraventricular block, hypertension, or a shunt. Then, if increased flow or increased pressure adds its effect to that of the bundle branch block, or if there is intraventricular block of the same side, the dissociation between the two ventricles may become so marked that actual splitting of the 1st sound may occur.

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2 *Prolongation of the total duration of the 1st sound,* which lasts beyond the peak of the C wave of the jugular tracing or the peak of the main wave of the carotid tracing The murmur is more prolonged

3. *Murmur in decrescendo* (Fig. 3-49B). This has larger vibrations at first, smaller vibrations later. It usually ends long before the 2d sound It is composed of vibrations of different pitches with predominance of the higher-pitched ones. It is typical of mitral regurgitation and is recorded best at the apex.

4 *Low-grade, all-systolic murmur,* usually made up of high-pitched vibrations It lasts

[16] The term "middiastolic murmur" is frequently inaccurate if used in descriptions of graphic tracings of diastolic murmurs A murmur is a prolonged series of vibrations Only in rare cases is diastole so long and the murmur so placed that such a term is justified

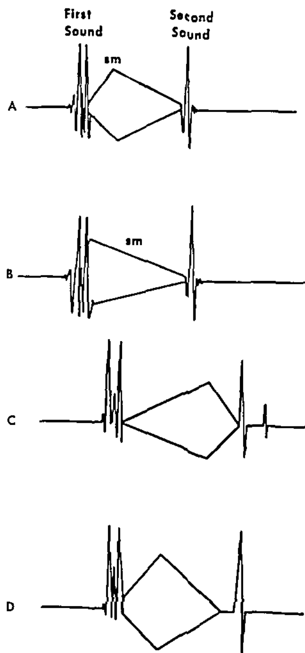


Fig. 3-49. Systolic murmurs· scheme. A Diamond-shaped, systolic murmur. B Systolic murmur in decrescendo. Aortic systolic murmurs may present a different coincidence between peak of the diamond-shaped murmur and phase of systole. C. Organic valvular stenosis: late peak. D Relative stenosis (dilatation of the aorta) or subaortic organic stenosis early peak.

throughout systole but does not cover the 2d sound It is recorded mostly at the apex and occurs in mitral regurgitation, especially in children. It is a rather uncommon type of murmur.

5 *Diamond-shaped* or *pulse-wavelike murmur*, typically recorded at the base (Fig. 3-49A). The vibrations start soon after the end of the 1st sound, increase toward the middle of systole, decrease later. They are made up of various frequencies with predominance of those in the medium range. The murmur is typical of absolute or relative stenosis of the aorta or pulmonary artery. The peak of the murmur corresponds to that of the pulse in the carotid tracing. Studies of Aravanis (1957) revealed that, in "relative stenosis," the peak of the murmur is usually in the first half of systole while, in organic stenosis, the peak falls *after* the middle of this phase. This fact is particularly apparent in severe stenosis, in which the peak occurs late in systole (Fig 3-49C). Congenital aortic stenosis, being usually of the subaortic type, may represent an exception (see below).

6. *Concertina-like murmur.* The vibrations show phases of greater and less intensity, all within a rather narrow band of frequencies The murmur is of maximum intensity over the midprecordium, is rather musical, and spreads in several directions It is found after a myocardial infarct (rupture of a chorda, mural thrombi) and in aortic stenosis with calcification

7. *Crescendo systolic murmur.* This is rare and may be found at the apex in mitral insufficiency or at the base in severe pulmonic or aortic stenosis. It may be an extracardiac murmur.

Basal Diastolic Murmurs. These are of two types

1 *Prolongation of the 2d aortic or pulmonic sound* The 2d sound is made up of three or four vibrations in decrescendo It is typical of slight aortic or pulmonic insufficiency, which may be connected with hypertension of the circulation involved

2 *Long diastolic murmur* This is typical of advanced aortic or pulmonic insufficiency (Figs 3-50A, 3-51, 3-53B). Usually the murmur starts immediately after the 2d sound and gradually decreases in intensity (*murmur in decrescendo*) during middiastole. If the vibrations are regular, there is a "sea-gull" or "cooing dove" type of murmur which is more common in, but not diagnostic of, an everted aortic valve In spite of the clinical impression of decrescendo, the murmur may have a *crescendo-decrescendo* appearance in the phonocardiogram The maximum amplitude takes place during the phase of rapid filling

inance of low-frequency vibrations (Fig 3-50B).

DIASTOLIC RUMBLE. Following the 2d sound, there is a short pause of silence, then an *opening snap* of the mitral valve This vibration is immediately followed by a variable number of irregular vibrations. These may be only three or four, or may continue throughout diastole, increase in presystole, and continue until the following 1st sound One or two louder vibrations may correspond to the peak of the wave of rapid filling and be the equivalent of the 3d sound (Fig 3-53A).

PRESYSTOLIC MURMUR. This corresponds to that short phase of diastole, preceding the 1st sound, during which atrial contraction occurs It is frequently a murmur *in crescendo* and its vibrations continue with those of the 1st sound The murmur usually *starts before the QRS wave of the ECG*, but most of it is during *early electrical systole* because of a delay of the 1st sound. The murmur includes vibrations of various frequencies with predominance of the low-pitched

Continuous Murmur. This type of murmur is typical of shunts between vessels. It frequently has the audible type of a *machinery* murmur and is found in patent ductus arteriosus and arteriovenous fistulas As first pointed out by Routier (1937), the murmur does not coincide exactly with the cardiac phases; it is usually *loudest at the end of systole, covers the 2d sound,* and *then decreases in diastole* (Fig. 3-52B). The frequency of the vibrations

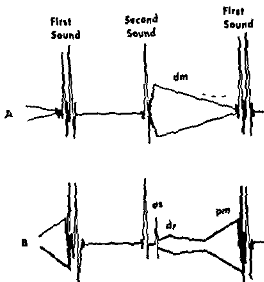


Fig. 3-50. Diastolic murmurs: scheme. A. Basal diastolic murmur in decrescendo. B Apical diastolic and presystolic murmurs. (From Luisada and Aravanis. M. Clin North America, 1957. Courtesy of W. B. Saunders Co.)

varies and several bands are usually represented. as proved by the use of different filters.

Other continuous murmurs include the thyroid murmur of Graves' disease, the venous hum of the neck, the murmur of a ruptured sinus of Valsalva, the murmur of an aneurysm of a coronary artery opening into the coronary sinus; occasionally the murmur of the common arterial trunk; the murmur which develops after a Blalock-Taussig or Potts operation; and that which has been recorded in stenosis of the peripheral branches of the pulmonary artery and in anomalous subclavian arteries.

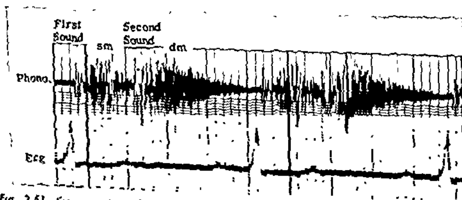


Fig 3-51. Extremely loud, harsh, diastolic murmur of aortic insufficiency, well recorded by means of a "stethoscopic" tracing There is also a systolic murmur.

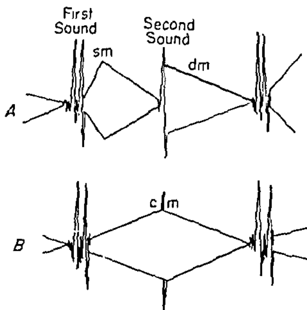


Fig. 3-52. A The double murmur of an aortic lesion. B. The continuous murmur (AV fistula, patent ductus). (From Luisada and Aravanis. M. Clin. North America, 1957. Courtesy of W. B Saunders Co.)

FRICTION RUBS

Pericardial friction rubs are revealed by the tracing as high-frequency vibrations, often grouped in three phases: presystole, midsystole, early diastole (Cossio et al, 1942) but *sometimes in only* two, i e., presystole and *systole (Fig. 3-54)*. Differentiation of rubs *from* murmurs is possible if no murmurs are present. On the other hand, if murmurs and rubs are both present, graphic differentiation *is almost* impossible.

ERRORS OF AUSCULTATION

Several errors of auscultation are due either to physiological inadequacies or to unavoidable clinical difficulties Some examples will be listed below *(Fig. 3-55)*.

1 *The* curve of sensitivity of the human ear *is such that sounds of increasing frequencies and of the same intensity are heard as louder and louder sounds.* This fact is easily revealed by phonocardiography which records the actual intensity of the vibrations. The high sensitivity of the ear for high-pitched sounds and its poor sensitivity for low-pitched sounds are revealed by one example observed in the authors' laboratory.

Following a myocardial infarct, a patient developed an apical systolic murmur which seemed loud. After a few days, a dull diastolic rumble was also noted, creating a puzzling problem. A phonocardiogram revealed the existence of a faint apical systolic murmur (relative mitral insufficiency) and a quadruple rhythm: two diastolic sounds of great intensity and low pitch gave the impression of a diastolic rumble.

2. Three phenomena, which may occur in presystole, are sometimes confused upon auscultation: the *atrial type of triple rhythm (gallop)*, the *presystolic murmur* of mitral stenosis, and a *crescendo type of the 1st sound* (usually an innocent aberration from the normal shape). Phonocardiographic tracings reveal the exact nature of the phenomenon without difficulty.

3. Clinical auscultation may reveal an abnormal sound in early diastole, the nature of which may not be clear. Phonocardiography will then reveal an opening snap of the mitral valve, a loud 3d sound (ventricular type of triple rhythm or gallop) or even a short diastolic rumble.

4. Another possible error is represented by the *systolic snap* Difficulty in the clinical timing of the 2d sound may lead to a diagnosis of mitral stenosis. the systolic snap is considered as a 2d sound while the 2d sound is considered as an opening snap of the mitral valve. Phonocardiography reveals the nature of the phenomenon

5. From time to time, clinical observers are baffled by an apparent *presystolic murmur* (an obvious impossibility) in patients with mitral stenosis and atrial fibrillation. Whenever there is a short diastole, the diastolic rumble becomes tumultuous and ends with the first sound of the following cycle. The ear will *register* a "presystolic" murmur.

6 Whenever there is *severe tachycardia*, systole and diastole may have the same duration. It may be difficult to decide by means of auscultation whether a soft, blowing murmur is systolic or diastolic. Phonocardiography reveals the phase of the murmur without difficulty

THE FUNCTIONAL MURMURS

The term "functional" murmur was created about a century ago in order to separate murmurs not caused by obvious valvular deformity from others. The most common instances were systolic murmurs of the apex or base of the heart which were encountered in severe anemia, pregnancy, or congestive failure, and which subsequently disappeared.

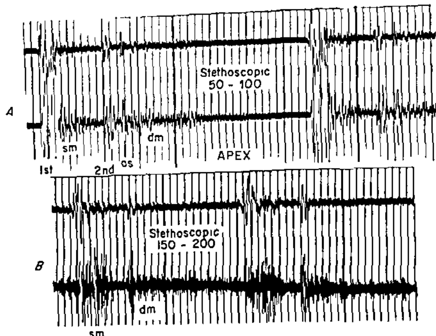


Fig. 3-53. A. Faint murmurs of mitral stenosis and insufficiency Above stethoscopic tracing; below. filtered tracing (bands 50 to 100 cps). Systolic murmur in decrescendo, opening snap, diastolic rumble at apex B. Faint murmurs of aortic insufficiency and stenosis Above stethoscopic tracing, below. filtered tracing (bands 150 to 200 cps). Diamond-shaped systolic murmur, decrescendo diastolic murmur, at base

In the last 30 years, some of the mechanisms causing functional murmurs have been clarified and can be summarized as follows:

Systolic Murmurs. There are four classes of these.

1. *Severe tachycardia* may cause a moderately loud murmur. Mechanism: probably multiple (acceleration of flow, incomplete valvular closure, etc)

2. *Severe anemia* may cause a loud apical or midprecordial murmur. Mechanism: probably multiple, including dilatation of the tricuspid and mitral rings (relative tricuspid and mitral insufficiency).

3. Conditions associated with increased blood volume (pregnancy), greater rapidity or quantity of systemic or sectional blood flow (hyperthyroidism, septal defects), or dilatation of one of the large arteries (aortitis, congenital dilatation of the pulmonary artery) frequently present a systolic murmur at the base. Mechanism: disproportion between normal ostium

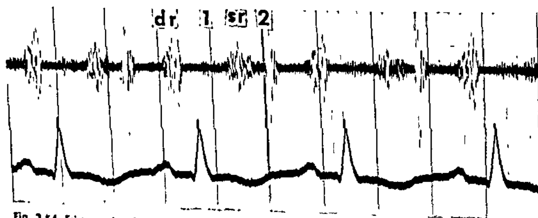


Fig. 3-54. Friction rubs dr = diastolic rub; sr = systolic rub.

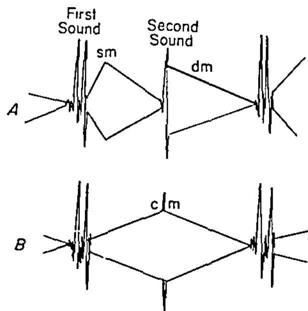


Fig. 3-52. A. The double murmur of an aortic lesion. B The continuous murmur (AV fistula, patent ductus). *(From Luisada and Aravanis M. Clin North America, 1957. Courtesy of W. B Saunders Co.)*

FRICTION RUBS

Pericardial friction rubs are revealed by the tracing as high-frequency vibrations, often grouped in three phases. presystole, midsystole, early diastole (Cossio et al., 1942) but *sometimes in only two, i.e., presystole* and systole (Fig 3-54). Differentiation of rubs from murmurs is possible if no murmurs are present. On the other hand, if murmurs and rubs are both present, graphic differentiation is almost impossible

ERRORS OF AUSCULTATION

Several errors of auscultation are due either to physiological inadequacies or to unavoidable clinical difficulties Some examples will be listed below (Fig. 3-55).

1 The curve of sensitivity of the human ear is such that *sounds of increasing frequencies and of the same intensity are heard as louder and louder sounds.* This fact is easily revealed by phonocardiography which records the actual intensity of the vibrations. The high sensitivity of the ear for high-pitched sounds and its poor sensitivity for low-pitched sounds are revealed by one example observed in the authors' laboratory.

Following a myocardial infarct, a patient developed an apical systolic murmur which seemed loud. After a few days, a dull diastolic rumble was also noted, creating a puzzling problem. A phonocardiogram revealed the existence of a faint apical systolic murmur (relative mitral insufficiency) and a quadruple rhythm: two diastolic sounds of great intensity and low pitch gave the impression of a diastolic rumble.

2. Three phenomena, which may occur in presystole, are sometimes confused upon auscultation: the *atrial type of triple rhythm (gallop)*, the *presystolic murmur* of mitral stenosis, and a *crescendo type of the 1st sound* (usually an innocent aberration from the normal shape). Phonocardiographic tracings reveal the exact nature of the phenomenon without difficulty

3 Clinical auscultation may reveal an abnormal sound in early diastole, the nature of which may not be clear. Phonocardiography will then reveal an opening snap of the mitral valve, a loud 3d sound (ventricular type of triple rhythm or gallop) or even a short diastolic rumble.

4. Another possible error is represented by the *systolic snap* Difficulty in the clinical timing of the 2d sound may lead to a diagnosis of mitral stenosis: the systolic snap is considered as a 2d sound while the 2d sound is considered as an opening snap of the mitral valve. Phonocardiography reveals *the nature of the* phenomenon

5. From time to time, clinical observers are baffled by an apparent *presystolic murmur* (an obvious impossibility) in patients with mitral stenosis and atrial fibrillation. Whenever there is a short diastole, the diastolic rumble *becomes tumultuous and ends* with the first sound of the following cycle The ear will register a "presystolic" murmur.

6 Whenever there is *severe tachycardia*, systole and diastole may have the same duration. It may be difficult to decide by means of auscultation whether a soft, blowing murmur is systolic or diastolic. Phonocardiography reveals the phase of the murmur without difficulty.

THE FUNCTIONAL MURMURS

The term "functional" murmur was created about a century ago in order to separate murmurs not caused by obvious valvular deformity from others The most common instances were systolic murmurs of the apex or base of the heart which were encountered in severe anemia, pregnancy, or congestive failure, and which subsequently disappeared.

Since then, many researchers have published fetal tracings with a gradually improved technique (Cesa and Seganti; Jordan and Randolph)

The method of fetal phonocardiography is relatively simple and far easier than fetal electrocardiography It permits evaluation of the rate of the fetal heart beat and even prenatal diagnosis of severe malformations of the heart

A stethoscopic microphone with a large chest piece is applied over that part of the maternal abdomen where auscultation reveals fetal heart tones. Simultaneously with the fetal sound tracing, a maternal electrocardiogram is recorded. Comparison of the two proves whether or not the sounds auscultéd were fetal heart tones

Esophageal Phonocardiography. Extensive studies with this method have been made by Taquini, by Miller and Groedel, and by Lian. Basis of interest in the method lies in the fact that the heart sounds are collected from inside the chest; their origin is near the collecting chamber, and their transmission is not altered by bony structures Thus, the 4th (atrial) sound takes place earlier than at the apex and may be due to the atrial contraction itself and not to its effect. The phonocardiogram is recorded by using a stomach tube closed at its end, similar to that employed for esophagocardiography. The most interesting tracing is that obtained at the atrial level. There, atrial sounds and mitral murmurs are more distinctly recorded than from the surface of the chest In general, sounds and murmurs have lower frequencies than when recorded by conventional techniques The heart sounds are shorter.

Tracheal Phonocardiography. Tracheal phonocardiograms have been recorded in patients by Groedel and Miller by means of a tracheal cannula The technique consists of connecting the outer end of the cannula with a microphone by means of a short piece of rubber tube The heart sounds are shorter and have vibrations of a lower frequency than when recorded from outside the chest

SUMMARY

Phonocardiography is both an auxiliary, bedside method of study to be used in conjunction with auscultation, and an independent graphic method which has the purpose of investigating the causes of cardiac sounds and murmurs.

Phonocardiography is based on the use of various microphones. The best results are obtained only by using adequate instrumentation.

Clinical phonocardiography yields diagnostic data through the use of selective filters Tracings in two bands (60 to 120 and 120 to 240 cps) are sufficient for the practical purpose of checking data obtained through auscultation A complete study requires, however, a graph obtained with a microphone which gives an accurate reproduction of the vibrations at the lower border of audibility and an amplifier-galvanometer system which exactly reproduces the high-pitched vibrations

Calibration has a certain value because it permits the recognition of the absolute intensity of the sound vibrations Both calibration of the apparatus and calibration of the patient are now possible.

It has been known for a long time that the auditory apparatus of man has several limitations which render it inadequate for cardiac auscultation because most of the vibrations set up by the heart are inaudible or poorly audible because of low pitch or low intensity. Even though cardiac murmurs are usually audible, several causes of error may render their perception, location, and description difficult and often debatable.

The normal heart sounds are four Two of them are always present at the beginning and end of ventricular systole (the 1st and 2d sounds), two others may be occasionally heard, and are more often recorded, during ventricular diastole (the 3d and 4th sounds).

The causes of triple rhythms (gallop rhythms) are discussed. Increased volume of either the 3d or the 4th sound is the most common cause of the diastolic types of triple rhythms An additional sound or snap in systole is the cause of the systolic type of triple rhythm

Splitting of the 2d sound is due to nonsimultaneous closure of the aortic and pulmonic valves This can be due to high pressure in the respective ventricle causing prolonged contraction and delayed closure of one valve. Ventricular hypertension may be caused by high pressure in one vessel (pulmonary artery, aorta) or stenosis of one valve (pulmonic valve, aortic valve). In the case of high vascular pressure, the delayed component is large, in the case of stenosis, the delayed component is small Splitting of the 2d sound can

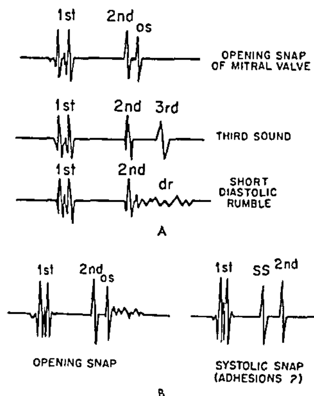


Fig. 3-55. Common pitfalls of auscultation. A. Opening snap (os) vs loud 3d sound (3d) or short diastolic rumble (dr) These phenomena are frequently confused upon auscultation. B. Opening snap (os) vs systolic snap (ss) difficulty in timing. (*From Luisada and Aravanis M. Clin. North America, 1957 Courtesy of W B Saunders Co.*)

and dilated vessel, trigonoidation of the valve (relative aortic or pulmonic stenosis)

4. Acute rheumatic carditis may cause a systolic apical murmur through congestion or edema of the mitral papillary muscles This would lead to either tension and vibration (musical murmur) or reversible shortening, a cause of valvular insufficiency (soft blowing murmur). It also may cause a basal systolic murmur through dilatation of the pulmonary artery.

The phonocardiogram may be of some help in differential diagnosis because it may reveal the following possibilities.

a. The vibrations of the murmur are extremely small, whatever the cause, the murmur is insignificant

b. The shape of the murmur reveals whether it is originating in one of the basal ostiums (diamond-shaped) or in one of the AV valves (decrescendo murmur).

Diastolic Murmurs. It has been known for a long time that patients with a normal mitral orifice may present a low-pitched diastolic or presystolic murmur which is indistinguishable upon auscultation from that of mitral stenosis Such a murmur has been described in aortic regurgitation, pericardial or hypertensive heart disease, rheumatic heart disease without mitral stenosis, and myocarditis.

Later on, phonocardiographic studies gave objective evidence of the existence and subsequent disappearance of the murmurs (Luisada et al., 1950; 1955). In some of the cases, the murmur was documented during life by the tracing, and autopsy disclosed that no mitral stenosis existed. In some of them, the tracing demonstrated that the diagnosis of mitral stenosis was due to an auscultatory illusion (diastolic extra sounds or crescendo type of 1st heart sound) while, in the others, the tracings did not reveal the functional nature of the murmur, and only the subsequent clinical course plus additional tracings proved that there was no mitral stenosis. Other graphic studies revealed a similar murmur in patent ductus arteriosus, rheumatic or congenital heart disease, or patients with an Austin Flint murmur

In a further study, certain *positive data* were found helpful in recognizing the functional nature of the murmur: in contrast with the murmur of mitral stenosis, this murmur is frequently made up of large vibrations and occurs in mid- or late diastole, it is often recorded over a large area of the chest; there frequently is a 3d sound Certain *negative data* were also found helpful. there is no opening snap and the main vibration of the 1st sound has a normal relationship with the QRS complex.

The murmur found in these patients seems to have been caused by a relative stenosis of the mitral valve or of both mitral and tricuspid valves (disproportion between normal ostium and large ventricle creating eddies within the ventricle). The large area of recording can be explained by the large area of contact with the precordium of the left ventricle (coronary and hypertensive cases), of the right (congenital heart disease), or of both ventricles (acute carditis)

SPECIAL APPLICATIONS OF PHONOCARDIOGRAPHY

Fetal Phonocardiogram. The first tracing of fetal sounds was recorded by Pestalozza (1891).

The 2d sound is probably transmitted from the heart (2d heart sound).

The sounds recorded over *the veins of the neck* are usually three. The presystolic sound is the loudest and it contains several vibrations. It may be due to transmission of the 4th sound of the heart through the upper mediastinum but distention of the vein in presystole is likely to be an important contributory factor. The sound coinciding with the C wave is probably of local origin. The third vibration is largely a transmission of the 2d heart sound.

Normal *peripheral arteries* reveal only one sound, e g, a multiple vibration at the time of maximum dilatation This sound becomes weaker and simpler in the more distal vessels More than one sound can be recorded, on the other hand, in clinical conditions (aortic insufficiency). Interesting considerations have been published by Rodbard

Records of sounds and murmurs from the peripheral arteries and veins are not part of the regular study of a cardiac patient. They may be used in individual cases either to obtain graphic evidence of unusual auscultatory phenomena or for research. It should be kept in mind that, occasionally, sounds and murmurs originating in the heart are recorded best in the neck, especially in obese and emphysematous patients (Fig. 3-56).

also be due to bundle branch block causing nonsimultaneous ventricular contraction and asynchronous closure of the arterial valves.

Actual splitting of the 1st sound is considered rare. Division of the large vibrations into two, or even three groups, within a prolonged 1st sound is, however, possible. The reasons for this fact are discussed

The characteristics of the cardiac murmurs are described Even though certain basal murmurs may have some vibrations in the high-frequency range (200 to 1,000 cps), the majority of loud vibrations is still in the medium range (between 100 and 200 cps). In addition to frequency and phase, the phonocardiogram also reveals the "shape" of the murmurs which has a definite diagnostic value Systolic and diastolic murmurs due to valvular lesions are also discussed.

Various errors of auscultation are listed While some of them are due to the physiological inadequacies of the auditory system, others are of psychological nature or due to difficulty in timing cardiac events. Several examples are quoted.

The problem of the "functional" murmur is discussed. Both systolic and diastolic murmurs may occur in patients with intact cardiac valves. Dilatation of the ventricles, the mitral and tricuspid rings, or the pulmonic or aortic vessels, can explain most of them. Graphic data which may help in the differential diagnosis of the various types of murmurs are listed.

SOUND TRACINGS OF PERIPHERAL VESSELS

HISTORY

While the peripheral arteries of normal subjects present no sounds, auscultation of the carotid and subclavian arteries reveals transmission of the heart sounds. Compression of an artery causes the appearance of sounds or blowing murmurs, a fact which has been used for recording blood pressure (Korotkov method). Arterial sounds over peripheral arteries or veins may be present in abnormal conditions. Sound tracings of peripheral arteries have been taken in order to obtain a graphic record of blood pressure or of special sound phenomena. Studies by Groedel and Miller of the phonocardiogram of the neck very likely include venous and arterial sounds of local origin

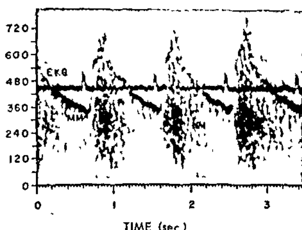


Fig. 3-56. Spectral phonocardiogram recorded over the left carotid bifurcation There is a noisy murmur with its peak at about the same time as the 2d heart sound which is faintly visible at 2. There is a continuous pure tone with changeable frequency level describing an arterial pulse pressure curve. MM, musical murmur; NM, noisy murmur. (From McKusick. Circulation, 1957.)

TECHNIQUE

The sound tracing from the arteries of the neck can be recorded by applying, over the carotid or subclavian artery, a microphone provided with a medium-sized funnel and held in place by a rubber strap A sound tracing from the veins of the neck can also be obtained by means of a suction cup connected to a linear and a stethoscopic microphone *Two simultaneous tracings* of sounds and pulsations are then obtained

A sound tracing from the arteries of the limbs can be obtained by using an apparatus described by Rappaport and Lusada The double cuff is wrapped around the limb The lower cuff is inflated to the desired pressure level after switching to "register" Simultaneous pulse and sound tracings are then obtained through a linear and a stethoscopic microphone

ANALYSIS OF THE WAVES

Two sounds are generally recorded *over the arteries of the neck.* The first of them occurs at the time of the rise of the pulse; the second, at the time of the incisura The 1st sound has several vibrations which are frequently divided into two groups: the first group slightly precedes the rise of the pulse and is due to transmission of the first part of the 1st heart sound, the second group coincides with the maximum dilatation of the vessel and is of local origin.

statistical standards for normal children at all ages including early infancy are those derived from the conventional multiple unipolar precordial leads. Two principal advantages are inherent in this method of examination:

1. The ability to specify with reasonable accuracy right and left ventricular size and their changing ratio, as in early infancy.

2. The ability, particularly in the case of the right ventricle, to detect evidence of physiological changes such as pressure, volume flow, and work, even in the absence of radiographic or other clinical (and sometimes anatomic) evidence of cardiac enlargement.

Except for systemic arterial pressures, no adequate *statistical* studies are available concerning direct physiological measurements in normal infants and young children However, electrocardiographic data supported by anatomical studies of the pulmonary vascular bed supply evidence for the presence in the neonatal period of normal children of right ventricular and pulmonary artery "hypertension" relative to measurements characteristic of later infancy and childhood. These normal pressure relationships are, in fact, such that during the neonatal period transient cyanosis may occur due to right-to-left shunting through the functionally patent, but valve-competent, foramen ovale without constituting evidence of actual cardiovascular disease Later on in childhood it is probable that normal physiological standards are quite similar to those published for young adults

It is generally agreed that so-called *functional, or innocent, murmurs* are very infrequently heard during early infancy, especially during the first 6 or perhaps 12 months after birth With few exceptions, therefore, any murmur which is heard during this period of time, in the absence of fever, anemia, etc , is probably organic but not necessarily permanent or of serious significance. After infancy, these nonorganic, innocent murmurs (so-called functional murmurs) have been defined, more or less arbitrarily, as having the following characteristics:

1. *Time in the cardiac cycle.* early-systolic, and usually decrescendo.

2. *Location:* maximum intensity at the upper left sternal border (2d or 3d intercostal space).

3. *Quality·* frequently vibratory, occasionally of high frequency ("blowing" murmurs).

4. *Intensity:* quite variable (this is not a very reliable criterion).

5 *Absence of significant transmission* over the precordium or thorax

6 *Variability·* may or may not disappear completely during deep inspiration, frequently louder with exertion.

7. Absence of other associated signs of heart disease, such as cardiac enlargement, other significant murmurs, abnormalities of heart sounds, etc.

It must be remembered that the *normal state* of anything is always difficult to define because, among other things, it is arbitrarily described within a certain range of statistical figures It must also be remembered that, especially in infancy and childhood, the "normal heart" is as much a dynamic as a static concept. A specific word of caution is therefore in order. namely, that such factors as growth and development, exercise tolerance, and resistance to infection, may be nearly as important as statistical data concerning the heart itself; and that, among the requirements for differentiating abnormal from normal, it is sometimes necessary to defer a decision until repeated observations have been made over a period of time rather than at just one examination, and always to exercise good, sound, correlative, clinical judgment

PHYSICAL EXAMINATION

The anatomical and physiological variations associated with the normal processes of growth and development are of paramount concern in the physical examination of the cardiovascular system of the infant and child Similarly, the alterations associated with disease processes, not necessarily cardiovascular in origin, produce extreme changes which require an even more critical evaluation than in the adult

The cardiologist, pediatrician, or family physician who evaluates the symptoms and signs suggesting cardiovascular disease, must be aware of and understand these factors in order to clinically differentiate cardiac from

I

Physical examination of the infant and child

The Normal Heart in Infancy and Childhood
ROBERT F. ZIEGLER

Physical Examination
JOSEPH R. CHRISTIAN

THE NORMAL HEART IN INFANCY AND CHILDHOOD

It is always important, but sometimes very difficult, especially in early infancy, to know just what constitutes a *normal* heart, such knowledge necessarily underlying one's ability to detect and properly evaluate abnormal variations One of the most important things to determine, both on its own account and for the contribution it makes toward the evaluation of such findings as cyanosis and heart murmurs, is *heart size*, assuming that practically without exception a diseased heart is an enlarged heart The contrary assumption, that a heart of normal size is therefore necessarily normal, is not valid, since there may be either some functional disturbance, such as abnormalities of impulse origin or transmission, or a structural abnormality of insufficient magnitude to be clinically detectable

Various static measurements of normal heart size as determined by conventional radiography are available. These, however, are subject to certain important limitations.

1. *Limitations of technique,* particularly in infants. While the phases of ordinary respiration make little difference in the x-ray appearance of the heart, forced expiration (as in crying) may produce the appearance of marked cardiac enlargement which disappears abruptly on deep inspiration. In this sense, fluoroscopic examination may frequently be more informative and reliable than routine radiography.

2 *Limitations of interpretation.* These include some standard difficulties, such as that of the superimposition of a large thymic shadow (especially in infants) and that of differentiating the factors of heart size versus position (high or low diaphragms, rotation, etc).

3 *Failure of the conventional chest x-ray to give evidence of ventricular hypertrophy,* especially without dilatation, and failure to distinguish specific right and left ventricular size, the relation between the two normally changing rapidly, particularly during infancy and early childhood

It might be noted in this regard that even anatomic measurements such as heart weight and right and left ventricular thickness, which are also available, are also subject to important limitations in the accurate differentiation of abnormal from normal heart size at any particular age

While it too is subject to certain important limitations, the most accurate means at present for establishing this differentiation is electrocardiography Furthermore, while there are proponents for such special techniques as spatial vectorcardiography, the most complete

relatively greater in this period than in later life. The neonatal lung is atelectatic and causes a perpetuation of the fetal horizontal position of the ribs at the costochondral and costovertebral junctions. The diaphragm is high, due to the relatively large size of the liver and to atelectatic lung Therefore, the heart lies in a higher and more nearly horizontal position in the thoracic cage.

The anteroposterior diameter of the chest is greatest in early infancy but, as growth increases, the lateral diameter also increases. The thinness, as well as the relative elasticity of the chest wall, tends to accentuate minimal cardiac or pulmonary change.

Polypnea in the neonatal period is the rule rather than the exception The normal rate of respiration in newborn and premature infants ranges from 35 to 45 *per minute*

Dyspnea is not a normal finding but it is increasingly more difficult to differentially diagnose in the newborn than *in the older* child. Dyspnea with fever and toxicity indicates pneumonia Dyspnea with fever, toxicity, and hoarseness indicates laryngotracheitis or laryngotracheobronchitis Dyspnea with wheezing, and no fever or toxicity, *indicates* asthma. Dyspnea with wheezing, *fever, and toxicity* indicates bronchiolitis

An increase in the respiratory *rate in an* infant or child, suspected of having *cardiac* disease but without previous *pulmonary disease*, strongly suggests cardiac decompensation The most delicate manifestation of cardiac decompensation is an increase in the respiratory rate

Cardiac Impulse. Visible pulsations, abnormal or exaggerated movements of the thoracic cage, and asymmetry of the chest are suggestive, if not diagnostic, of ventricular hypertrophy, aortic abnormalities, or organic heart disease

Ventricular hypertrophy can be readily detected by observing the thoracic configuration and the quality and position of the apical thrust This is especially *true in* infants When the right ventricle increases in size, there is a leftward rotation of the cardiac mass resulting in a prominence of the left side of the chest and a very diffuse apical beat which may extend from the 4th to the 6th *intercostal* space and from the midclavicular line to the anterior axillary line. The impulse may be so intense that a precordial thrust rather than an apical beat is noted.

The apical beat is usually limited to one intercostal space in the midclavicular line. The younger the infant, the higher the point of greatest intensity because of the semihorizontal or horizontal position of the heart.

When the left ventricle enlarges, there is a dextrorotation of the heart and the left chest does not become as prominent, but the apical beat is usually lower and more lateral than with right ventricular hypertrophy.

Prominent pulsations at the suprasternal notch suggest pathologic change in the aorta, i e , an aortic aneurysm (rare in infancy and childhood), coarctation of the aorta (a *more* common congenital defect), or aortic insufficiency (the most common organic disorder involving the aorta). All these disorders can be *readily* confirmed by means of palpation, auscultation, and confirmatory laboratory studies.

PERCUSSION

Percussion of the chest is one of the most difficult and fruitless tasks for the pediatrician In the neonatal period, the anatomical relationships are such that the criteria and methods applicable to the adult and older child cannot be successfully utilized. Also, in the obese infant and child, the thick layers of subcutaneous fat interfere with percussion *Direct percussion*, rather than indirect, which is only *forceful* enough to elicit a perceptible sound, is more suitable *for the pediatric* group Forceful direct or indirect percussion *produces* vibrating tones from organs or tissues in *close* proximity and masks the interpretation

Obvious congenital abnormalities, such as *dextrocardia* or *situs inversus*, can usually be discovered by *direct* percussion. However, *more subtle* changes in cardiac size, position, or configuration cannot be *revealed* by direct or indirect percussion.

The most successful results have been produced by *a combination of auscultation and direct percussion.* A small diaphragm-type stethoscope is placed over the organ *or mass* in question Direct percussion with the index or middle finger, just forceful enough to *elicit* a sound, is delivered at right angles and *peripheral* to the presumed border. The finger is advanced toward the stetho-

noncardiac disease. A critical analysis of the symptoms presented in the history and of the signs disclosed by the physical examination reveals the path for laboratory diagnostic studies required to confirm the clinical diagnosis.

Numerous and widely divergent approaches to cardiovascular disease in the earlier years of life have been proposed. However, the scrutinizing eyes, delicate touch, and perceptive ears of the clinician are by far the most important and significant factors in the diagnosis of cardiovascular disease.

INSPECTION

The initial bedside appraisal of the patient can and should be the most rewarding part of the physical examination to the clinician. Time and patience are essential and usually result in the gathering of surprisingly useful data.

Color of the Skin. With the relatively unstable vasomotor mechanism of the newborn, and especially of the premature infant, it is extremely difficult to evaluate cyanosis during the first few hours of life However, in the succeeding period, *cyanosis* is more readily discernible. The intensity, distribution, consistency, and association with clubbing are by far more significant than the mere notation of cyanosis.

The greater the intensity of cyanosis, the greater the amount of blood being shunted from the venous to the arterial circulation. When extreme cyanosis occurs in the neonatal period, one must consider the possibilities of complete transposition of the great vessels, severe tetralogy of Fallot, tricuspid atresia with a nonfunctioning right ventricle, pulmonary stenosis, Taussig-Bing syndrome, truncus arteriosus, or aortic atresia. However, as age increases, the possibilities decrease, and the tetralogy of Fallot or the Taussig-Bing syndrome become the most probable

If the head, upper trunk, and upper extremities are intensely cyanotic but *the lower segments are less or not cyanotic*, one should suspect transposition of the great vessels with a patent ductus arteriosus carrying oxygenated blood to the descending aorta On the other hand, *if the cyanosis is localized in the lower portions of the body*, an interruption of the aorta or an infantile type of coarctation with venous blood entering the descending aorta, should be considered.

The combination of cyanosis and clubbing is practically *never* seen in early infancy. Cyanosis must be present for a considerable length of time before clubbing occurs, the minimum time being 4 to 5 months.

Obvious cyanosis is not as much a problem as doubtful cyanosis. The quiet infant or child is easy to examine but does not give the examiner as much information as the crying patient, especially in the evaluation of cyanosis Intensification of cyanosis with crying, almost immediately removes the possibility of a pulmonary or neurogenic mechanism

Pallor, associated with nutritional deficiency states, suggests an iron deficiency or nutritional anemia. However, patients with rheumatic fever consistently demonstrate certain classical characteristics. The skin is fair, somewhat thin, with a prominent venous pattern, most outstanding on the face and trunk, and a butterfly and perioral pallor. This pallor is out of proportion to the hemoglobin level, for only infrequently do children with rheumatic fever have a hemoglobin level under 11 or 12 Gm

Erythema annulare, the characteristic skin lesion of rheumatic fever, is readily seen on the trunk and extremities. It is a salmon-pink color with well-circumscribed borders that are slightly raised and somewhat clearer in the central area. The rash is evanescent, may last from several minutes to several days, and is usually associated with other vasomotor phenomena such as blushing and flushing Occasionally, but frequently enough to be noteworthy, the patient with rheumatic fever who manifests erythema annulare has, or has had, an episode of *dermatographism*.

Rheumatic nodules, also a characteristic lesion of rheumatic fever, are nontender, rounded masses, varying in size from 0.2 to 2 cm in diameter They are usually located on the extensor surfaces of the extremities along the dorsal spine and scalp Their presence indicates a severe infection and invariably a more severe cardiac involvement. These lesions usually can be seen more readily than palpated

Type of Respiration. The relative size and shape of the thoracic cage of the infant and child is markedly different from that of the adult The cardiac and hepatic proportions are

relatively greater in this period than in later life. The neonatal lung is atelectatic and causes a perpetuation of the fetal horizontal position of the ribs at the costochondral and costovertebral junctions The diaphragm is high, due to the relatively large size of the liver and to atelectatic lung Therefore, the heart lies in a higher and more nearly horizontal position in the thoracic cage

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Color of the Skin. With the relatively unstable vasomotor mechanism of the newborn, and especially of the premature infant, it is extremely difficult to evaluate cyanosis during the first few hours of life. However, in the succeeding period, *cyanosis* is more readily discernible The intensity, distribution, consistency, and association with clubbing are by far more significant than the mere notation of cyanosis.

The greater the intensity of cyanosis, the greater the amount of blood being shunted from the venous to the arterial circulation. When extreme cyanosis occurs in the neonatal period, one must consider the possibilities of complete transposition of the great vessels, severe tetralogy of Fallot, tricuspid atresia with a nonfunctioning right ventricle, pulmonary stenosis, Taussig-Bing syndrome, truncus arteriosus, or aortic atresia However, as age increases, the possibilities decrease, and the tetralogy of Fallot or the Taussig-Bing syndrome become the most probable

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Polypnea in the neonatal period is the rule rather than the exception The normal rate of respiration in newborn and premature infants ranges from 35 to 45 per minute

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Percussion of the chest is one of the most difficult and fruitless tasks for the pediatrician. In the neonatal period, the anatomical relationships are such that the criteria and methods applicable to the adult and older child cannot be successfully utilized. Also, in the obese infant and child, the thick layers of subcutaneous fat interfere with percussion *Direct percussion*, rather than indirect, which is only forceful enough to elicit a perceptible sound, is more suitable for the pediatric group Forceful direct or indirect percussion produces vibrating tones from organs or tissues in close proximity and masks the interpretation.

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The greater the intensity of cyanosis, the greater the amount of blood being shunted from the venous to the arterial circulation When extreme cyanosis occurs in the neonatal period, one must consider the possibilities of complete transposition of the great vessels, severe tetralogy of Fallot, tricuspid atresia with a nonfunctioning right ventricle, pulmonary stenosis, Taussig-Bing syndrome, truncus arteriosus, or aortic atresia. However, as age increases, the possibilities decrease, and the tetralogy of Fallot or the Taussig-Bing syndrome become the most probable

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scope diaphragm and the point of change from resonance to dullness is noted and indicates the border of the organ or mass. Complete rotation over the area will designate size, shape, and position. To confirm the findings, the fingernail should be scratched from the periphery toward the stethoscope and a similar change of sound will be noted. This method has proved to be the most informative and advantageous form of percussion.

A note of caution: the change of position from supine to sitting produces considerable displacement of abdominal viscera and thoracic organs and results in completely different results. Therefore, all infants and children who are examined by this method should be placed in the same position routinely so that consistent results may be obtained.

PALPATION

The *cardiac impulse* can be distinguished more readily by palpation than by inspection alone. However, much more can be deduced by starting at the periphery and proceeding from the extremities to the abdomen, then to the head and neck, and, finally, to the chest.

The greatest satisfaction in palpating *weak femoral pulses* is in knowing that the diagnosis of coarctation of the aorta can be founded well on this fact alone. However, aortic atresia results in *weak radial,* as well as femoral, pulses. Therefore, palpation of the radial pulse can instantly confirm or rule out a coarctation of the aorta, which is always accompanied by forceful radial pulsations.

In palpating the femoral pulse of the newborn infant, extreme gentleness, a warm hand, and a quiet, relaxed patient can give more information in a few seconds than minutes of struggling with a screaming, kicking infant.

A *palpable liver margin* is the rule in the newborn child. Therefore, this constant physical finding of right heart failure in the older child or adult with cardiac decompensation, is relatively valueless in the neonatal period. However, *pulsation of the liver edge* is diagnostic of a tricuspid valvular abnormality. Tricuspid insufficiency, stenosis, or atresia result in pulsation of the liver. The timing of the pulsation varies with the type of disease, i.e., insufficiency of the tricuspid valve results in a *systolic pulsation;* stenosis or atresia with a well-formed atrial septum or a small interatrial defect, results in a *presystolic pulsation.* Occasionally, pulmonary stenosis with an intact ventricular system may produce a pulsating liver.

Palpation of the radial pulse supplies a method by which a patient can be readily and rapidly appraised with regard to the state of circulation or abnormalities of rate and rhythm, i.e., pulsus alternans, pulsus bigeminus, atrial fibrillation, extrasystoles, etc.

Pulsation of abnormal intensity in the suprasternal notch, the supraclavicular regions, or both, is suggestive of aortic aneurysm, aortic regurgitation, or hypertension, in children as well as in adults. However, an infant or child with hyperpyrexia may have visible and palpable pulsations of such extreme intensity that the entire body seems to pulsate with each cardiac impetus. This may or may not be associated with cardiac disease.

A *thrill* is the palpable vibratory transmission of an abnormal heart murmur and presupposes a disturbance of hemodynamics. Basa thrills are most readily palpated in the sitting position; apical thrills, in left lateral position. The intensity, position and phase of the thril in the cardiac cycle are of utmost importanc in their diagnostic implication. *Presystolic o diastolic thrills* are rarely, if ever, palpated i the newborn period or during the first fe months of life. Diastolic thrills are almost com pletely limited to the adult group of patient These are apical in position and indicate mitr stenosis. In childhood, mitral stenosis rarel if ever, occurs without regurgitation and almost always due to rheumatic carditis. Th thrill is presystolic and apical.

The *systolic thrill* in the suprasternal notc suggests aortic or subaortic stenosis. The thr in the 2d intercostal space along the left stern border suggests an interatrial septal defe *A continuous thrill* in the 2d intercostal spac but occasionally over the entire basal area, suggestive of a patent ductus arteriosus.

Sphygmomanometric determination of th arterial blood pressure is an integral part any physical examination. However, in vie of a significant variation due to congenital acquired heart disease, the determinatio should be made on all four extremities and cuff of appropriate size should be applied. A adult cuff, when used on an infant or chil will give abnormally low pressure readings; infant cuff, when used on an adolescent, w give an abnormally high reading.

The auscultatory method of blood pressu determination should be preferred to the palp

tory. Especially in the newborn infant, there is a tendency to exert too great a pressure on the peripheral artery and compression results in an inaccurate determination.

Normally the *systolic pressure* ranges from 85 to 90 mm Hg and the *diastolic* between 58 and 60 mm during the first 5 years of life. From 5 to 10 years of age, the systolic pressure increases about 10 mm and the diastolic 5 mm. Between 10 and 15 years the systolic rise is 10 to 15 mm and the diastolic rise 5 to 10 mm. The pulse pressure averages between 25 and 35 mm for all age groups

Elevation of the systolic pressure is usually *secondary* to renal disease, adrenal tumors, aortic insufficiency, coarctation of the aorta, or patent ductus arteriosus In aortic insufficiency and patent ductus arteriosus, the diastolic pressure is markedly lowered due to the insufficiency of the vascular channels. Extreme crying, straining, etc, can produce as much as a 30- to 40-mm rise in pressure Therefore, care should be taken to obtain accurate blood pressure determinations only when the infant or child is at rest.

AUSCULTATION

If inspection, palpation, and percussion have been carefully performed, auscultation of the cardiac sounds can be interpreted more readily and efficiently.

From infancy to adulthood, the size, shape, and position of the heart undergo extreme variations. Also, the lung and the thoracic cage undergo similar anatomical changes As these variations are most pronounced in infancy, the interpretation of the quality, intensity, and transmission of a cardiac sound may be erroneously interpreted. This is especially true in the newborn child whose heart is small and chest wall thin. A cardiac murmur in this group may be so widely transmitted over the entire precordium that it is difficult to distinguish whether it is basal or apical in origin Furthermore, the differentiation between a congenital and acquired organic murmur purely on the basis of quality, intensity, or transmission is impossible.

The first and most fundamental step in the auscultation of the heart is to determine *the rate* and *rhythm* The rate is inversely proportional to the age of the patient. The sequence of sounds, irrespective of age, is a *three-quarter* or *waltz-time rhythm*. Disturbances in the rate, rhythm, or both are suggestive of acquired organic disease rather than congenital cardiac disease, with the exception of congenital defects involving the conducting system.

The heart sounds are produced by the complex mechanism of the musculovalvular elements of the heart (Part 2). The 1st sound has a rather low-pitched quality and is of greater duration than the 2d sound, in adults. However, the 1st and 2d sounds are of equal intensity at birth and during the early period of infancy, and they may be so rapid that occasionally it is not possible to differentiate the 1st sound from the 2d As age increases, the 1st sound becomes louder at the apex and the 2d sound increases at the base. The rapid rate and equal intensity of the sounds in the newborn produce a tic-tac type of rhythm or *embryocardia*, similar to that heard in the fetus. In any period other than early infancy, this rhythm is suggestive of severe organic heart *disease*

The intensity of the 1st sound is greatest in the mitral or apical areas. In the tricuspid area, the 1st sound is accentuated but less intensely than in the mitral area. Conversely, in the aortic and pulmonic areas, the 1st sound is least intense

Accentuation of the 1st sound suggests an irregularity of the rhythm such as atrial fibrillation, extrasystoles, sinus arrhythmia, or heart block. This may be difficult to determine in the infant or young child, and palpation of the carotid impulse may greatly assist in the timing. The carotid impulse is almost synchronous with the 1st heart sound.

The 2d sound has a higher pitch but is of shorter duration than the 1st It is most intense at the base *with the pulmonic sound greater than the aortic*. However, the aortic valve usually closes just prior to the pulmonic valve and a *split second sound results*. This is the rule rather than the exception in infants and children It is so characteristic that the *absence of splitting* can be interpreted as being due to pulm…

… suggests an interatrial septal defect with *left-to-right* shunt.

The 3d heart sound is characteristic of children or adults with a thin chest wall. It is best

scope diaphragm and the point of change from resonance to dulness is noted and indicates the border of the organ or mass. *Complete rotation* over the area will designate size, shape, and position. To confirm the findings, the fingernail should be scratched from the periphery toward the stethoscope and a similar change of sound will be noted. *This method has proved to be the most informative and advantageous form of percussion.*

A note of caution: the change of position from supine to sitting produces considerable displacement of abdominal viscera and thoracic organs and results in completely different results. Therefore, all infants and children who *are examined by this method* should be placed in the same position routinely so that consistent results may be obtained.

PALPATION

The *cardiac impulse* can be distinguished more readily by palpation than by *inspection* alone. However, much more can be deduced *by starting at the periphery and proceeding* from the extremities to the abdomen, *then to* the head and neck, and, *finally, to the chest.*

The greatest satisfaction in palpating weak femoral pulses is in knowing that the *diagnosis* of coarctation of the aorta *can be founded* well on this fact alone. However, aortic atresia *results in weak radial,* as well *as femoral,* pulses. Therefore, palpation of the *radial pulse* can instantly *confirm or rule* out a coarctation *of the aorta,* which is always accompanied by forceful radial pulsations.

In palpating the femoral *pulse of the newborn infant,* extreme gentleness, a warm hand, and a quiet, relaxed patient can give more information in a few seconds than minutes of struggling with a screaming, kicking infant

A *palpable liver margin* is the rule in the newborn child Therefore, this constant physical finding of right heart failure *in the older* child or adult with *cardiac* decompensation, is *relatively* valueless in the neonatal period. However, *pulsation of the liver edge is diagnostic* of a tricuspid valvular abnormality. Tricuspid insufficiency, *stenosis,* or atresia result in pulsation of the liver. The timing of the pulsation varies with the type of disease, i.e., insufficiency of the tricuspid valve results in a *systolic pulsation, stenosis* or atresia with a well-formed atrial septum or a small interatrial defect, results in a *presystolic pulsation.* Occasionally, pulmonary stenosis with an intact ventricular system may produce a pulsating liver.

Palpation of the radial pulse supplies a method by which a patient can be readily and *rapidly appraised* with regard to the state of circulation or abnormalities of rate and rhythm, i.e., pulsus alternans, pulsus bigeminus, atrial fibrillation, extrasystoles, etc.

Pulsation of abnormal intensity in the suprasternal notch, the supraclavicular *regions, or* both, is *suggestive of aortic* aneurysm, aortic *regurgitation,* or hypertension, in children as well as in adults. However, an infant or child with hyperpyrexia may have visible and palpable pulsations of such extreme intensity that the entire body seems to pulsate with each cardiac impetus. This may or may not be associated with cardiac disease.

A *thrill* is the palpable vibratory transmission of an abnormal heart murmur and presupposes a *disturbance of hemodynamics.* Basal thrills are most readily palpated in the sitting position; apical thrills, in left lateral position The intensity, position and phase of the thrill in the cardiac cycle are of utmost importance in their diagnostic implication *Presystolic or diastolic thrills* are rarely, if ever, palpated in the newborn period or during the first few months of life. Diastolic thrills are almost completely limited to the adult group of patients These are apical in position and indicate mitral stenosis. In childhood, mitral stenosis rarely, if ever, occurs without regurgitation and is almost always due to rheumatic carditis. This thrill is presystolic and apical.

The *systolic thrill* in the suprasternal notch suggests aortic or subaortic stenosis. The thrill in the 2d intercostal space along the left sternal border suggests an interatrial septal defect. *A continuous thrill* in the 2d intercostal space, but occasionally over the entire basal area, is suggestive of a patent ductus arteriosus.

Sphygmomanometric determination of the arterial blood pressure is an integral part of any physical examination However, in view of a significant variation due to congenital or acquired heart disease, the determinations should be made on all four extremities and a cuff of appropriate size should be applied. An adult cuff, when used on an infant or child, will give abnormally low pressure readings, an infant cuff, when used on an adolescent, will give an abnormally high reading.

The auscultatory method of blood pressure determination should be preferred to the palpa-

11

Functional capacity of the cardiovascular system

The Heart

ALBERT S. HYMAN

The Arterial Circulation

DAVID I. ABRAMSON

THE HEART

It is almost 100 years since Stokes called attention to the "wondrous differences which the heart manifests on turning from rest to labour." The concept of the dual role of the cardiovascular system at rest and at work, while well-recognized over the years, has, strangely enough, not received the attention from internists and cardiologists which modern medicine demands. Many authors have pointed out that the clinical evaluation of the resting heart may have no objective relationship to the same cardiovascular system under physical stress There may be no correlation, for example, between grossly abnormal electrocardiograms and a patient's functional capacity for work performance, the electrocardiogram per se permits no appraisal of potential or inherent cardiac activity.

The other side of the picture is equally true A patient comes to his physician complaining of severe pain and dyspnea, a complete examination (including an ECG, x-ray studies, a ballistocardiogram, vital capacity determination, and other standard procedures, as well as laboratory tests) may have been within normal limits Having been reassured, the patient leaves the office or clinic in a happier mood only to reexperience his pain and dyspnea on the first flight of stairs he encounters on the way home He may well ask why he develops such incapacitating symptoms when all of the tests made at the time of the examination indicated that he was normal The answer must be based on the concept that the cardiovascular system at rest and at work may in such instances become two separate and distinct entities, the patient developed his disability while *in action* but he had been examined only *at rest*. If the same tests had been made during the time that he was experiencing his pain and dyspnea, the physician might have been no little startled by the data obtained

There is nothing new in this thought The concept of *cardiovascular dualism* originated with the Viennese school of cardiology about 50 years ago· Wenckebach and Winterberg, Kaufmann and Rothberger, and Eppinger and Hess all emphasized the role of *exercise* in the diagnosis of heart disease Schneider (1918) revised the test to include other data

The *Hyman-Opitz Index* was devised in 1939. It had been recognized by all military services that examination of the working heart had far greater clinical implications than that of the cardiovascular system at rest Within certain limitations, a dual examination of the cardiovascular system can play an equally important role in general medicine These limitations are predicated upon the inherent differences between the two groups: whereas military personnel consists mostly of healthy young adults with no heart disease, persons

heard at the apex with the patient in a supine or left lateral position Because of a lower pitch and decreased intensity, a bell-type stethoscope is preferable.

When associated with tachycardia, the 3d heart sound becomes loud and causes the appearance of a gallop or *triple rhythm*. A simple clinical method of differentiating a significant from a nonsignificant type of triple rhythm is to sedate the infant sufficiently to decrease the cardiac rate. With the slowing of the cardiac rate, a distinctness of the sounds and disappearance of the extra sound can be readily appreciated in the normal heart but fails to be disclosed in the pathological state.

An abnormality of rhythm associated with an increased rate is suggestive of organic heart disease This is usually manifested by a rumbling or muffling of sounds associated with a change of intensity The distinctness of the tones is lost

The *second fundamental step* in the auscultation of the heart is to separate the normal from the abnormal sounds and categorize them according to causation Even though the human ear is not able to differentiate changes of intensity from changes of pitch, it is quite often able to recognize the origin of the abnormal sounds

When a murmur is detected and the cardiac rate is over 120, systole and diastole are readily confused. Also, if systole and diastole are of equal intensity, localization of the murmur is difficult. These problems are readily resolved by starting auscultation away from the area in which the murmur is of greatest intensity, i e., basal area for apical murmurs and apical area for basal murmurs This allows the examiner to distinguish the 1st and 2d sounds more clearly. Timing of the murmur can then be accomplished as the stethoscope is advanced toward the point of maximum intensity

Febrile illnesses associated with extremely toxic states can increase blood velocity and cardiac rate to a point where a murmur is produced This is usually *systolic* in time, *apical* in origin and about grade 2 to 4 in intensity

Decreased viscosity associated with an anemia produces a similar murmur. However, this *hemic murmur* is extremely intense when the hemoglobin is less than 5 Gm, and the murmur is transmitted to the neck and temporal regions via the temporal artery.

Eddy currents, positional changes, etc., can all be responsible for the production of similar abnormalities of sound. On occasion, the cause is undetermined but, rather than classifying these abnormal sounds as "functional," the terms "unexplainable" or "unclassifiable" should be used.

The only significant organic murmurs in childhood are those caused by *rheumatic fever* Mitral stenosis does not occur in childhood, therefore, when a diastolic apical murmur is heard, it is usually due to an *active carditis* through a "functional," though pathological, mechanism. The soft, blowing, *apical systolic murmur*, which occasionally has a high-pitched, "cooing" quality, and the loud *diastolic murmur*, which is transmitted from the 2d right interspace downward along the left border of the sternum, are characteristic of rheumatic mitral and aortic valvulitis, respectively.

Several congenital cardiac abnormalities are accompanied by significant murmurs, which are diagnostic of the abnormality present

Patent ductus arteriosus is concomitant with a continuous, blowing or machinery-like systolic and diastolic murmur, heard best in the 2d left intercostal space.

Ventricular septal defect is characterized by a coarse and loud systolic murmur heard best in the 3d to 4th left intercostal spaces

Atrial septal defect can be diagnosed by a systolic murmur heard best in the 2d to 3d intercostal spaces, which is less intense than that heard with a ventricular defect but without the blowing quality of the ductus.

Aortic or subaortic stenosis is characterized by a loud systolic murmur, heard best in the 2d right intercostal space, harsh in quality and transmitted to the neck and shoulders

Pulmonic or subpulmonic stenosis is accompanied by a loud systolic murmur, heard best in the 2d or 3d left interspace, harsh in quality and transmitted to the left clavicle and the back.

The murmurs heard in the remaining congenital defects that produce murmurs do not have a characteristic quality, position, transmission, etc , therefore, they cannot be considered diagnostic.

to fall off the steps, this is also true of individuals with unsteady gait.

Various authors have recommended different amounts of work performance; there are 5,000, 10,000, and 20,000-ft-lb standards in current use. Master developed a scale of work performance based on weight, age, and sex. In the author's work, he has used the 5,000-ft-lb standard for all function tests.

No effort test should ever be performed after a meal, ingestion of food can produce electrocardiographic as well as other changes. Cold drinks are also forbidden for a similar reason. Smoking may interfere with the test.

Patients must be carefully watched throughout the test, particularly those of groups 1 and 2 The onset of dyspnea, the development of pain, or both, are signs indicating that the test should be terminated or continued with caution, the patient's willingness to continue is a valuable guide. The examiner, after some experience, will be able to estimate just how far a given patient may go, the test will be more informative if the individual can complete the standard work performance test, even if symptoms do occur

The specific test under investigation must be made directly after the exercise is performed, certain changes, like those associated with heart size and the arteriogram, may disappear within 60 sec Time is truly of the essence here and much valuable data may be lost if there is any appreciable delay in examining the individual. A well-planned routine is mandatory if the test is to be exploited to its utmost.

After the subject has rested for a 5-min period, the specific test under study is repeated The pre-exercise, postexercise, and 5-min records are then compared, ordinarily, in all of the function tests the [illegible] orig [illegible] the [illegible] at the end of 10 or even 30 min, some electrocardiograms may require a longer [illegible] also true [illegible] cardiogra[illegible] be consid[illegible] the patient has returned to the *status quo ante* A delay in the return to "normal" constitutes an important part of the test

Five specific tests lend themselves to dual examination, even though there are a number of other procedures which may be employed. The physiological test is simple and should be selected if only one test is permitted The electrocardiogram, the arteriogram, the determination of heart size by x-ray examination, and the ballistocardiogram, constitute the other four.

PHYSIOLOGICAL TESTS

The *Crampton test*, *Schneider index*, and *Hyman-Opitz (H-O) test* were used as cardiovascular screening tests by the Armed Forces. Since these tests were chiefly employed in the age group from 18 to 28, an age-equalizing factor became necessary before the procedure could be adapted for clinical medicine. The so-called *Hyman cardiopulmonary index* can thus be utilized as a measure of cardiac function at rest and after exercise

The test consists of the mathematical addition of vital capacity, VC (in 100 ml), plus breath-holding, *BH* (in seconds), plus pressure breathing, PB (in mm Hg), plus age (in years), *divided* by systolic pressure, SP (in mm Hg), plus diastolic pressure, *DP* (in mm Hg), plus pulse rate, *PR* (per minute) The formula thus becomes:

$$\text{Cardiopulmonary index} = \frac{VC + BH + PB + \text{Age}}{SP + DP + PR}$$

The normal CP index has been established as 1 000 (plus or minus 10 per cent) from data secured from military sources and college students *A reduction in the resting index to 0 750 or below suggests cardiovascular functional disability.* The test is valid only in the absence of pulmonary disease The test is used in the following way

A given patient shows these clinical findings.

Age	52
Vital capacity	33
Breath holding	60
Pressure breathing	90
	235
Systolic pressure	142
Diastolic pressure	86
Pulse rate	84
	312

$$\text{or } \frac{235}{312} = 0\,752 \text{ (CP index)}$$

An index of 0 752 is within the marginal area of initial loss of functional capacity

Performance of the standard 5,000 ft-lb of work yielded the following data

Age	52
Vital capacity	25
Breath holding	30
Pressure breathing	70
	177

who seek medical care are usually in the older age groups with more or less obvious *signs of the failing heart of middle life.* An effort test, simple for the first group, *may be a hazardous* performance for individuals with a *poorly* functioning coronary system or elevated blood *pressure.*

SELECTION OF PATIENTS FOR THE FUNCTION TESTS

Indications for the dual *examination* have *become rather clearly defined for most patients; sufficient* experience has been *gained* during the past 15 years to limit the calculated risk *associated* with exercise tolerance tests. *The previous* prejudice against exercising *cardiac patients* has largely disappeared. These patients are classified *in four groups.*

Group 1 consists of patients who have advanced cardiovascular disability and *many objective findings of heart disease*; these include *grossly* abnormal ECG, *enlargement* of the heart as determined by x-ray examination, hypertension, congestive failure, and a limited capacity for effort. These patients are obviously not suitable candidates for an exercise *tolerance test since they* are unable to carry *on with their ordinary* daily activities without *symptoms. In certain* instances, however, it *may* be possible *to undertake one* or more of the *special* function tests, provided the *necessary* precautions are taken. The information *thus gained may* have a significant bearing on treatment and *prognosis.*

Group 2 is concerned with patients with definitive abnormalities in one or more of the *special* cardiological tests but *who present minimal* subjective symptoms Such individuals *invariably* desire detailed information about the extent of their activities, *most of them* wish to *do more than* the physician has previously *advised. Here the* good judgment and *experience of* the examiner must play an important part *in determining* the need for the dual examination but it is in this very type of case where the procedure is most valuable to both the patient and the clinician.

Group 3 consists chiefly of patients with a minimum of objective pathological signs but with a long list of subjective *complaints. With* few exceptions, such *individuals present* no risk, and the dual tests may provide the *necessary clues in distinguishing* between *psychosomatic syndromes* and *those* based upon *actual functional disability.* The dual tests have *proved to be of great* value in the *management of this difficult clinical* group which may consist of insurance and industrial compensation claimants with their special motivation problems.

Group 4 is a miscellaneous group including individuals with concealed cardiovascular disabilities attempting to pass physical examinations: a man may wish to obtain insurance by denying previous heart disease; an athlete may wish to conceal a cardiac condition; a laborer may wish to apply for a job beyond his physical capacity because of heart involvement. Civil service candidates, for the police or fire departments or school system, with unknown or concealed heart disease, come within *this group. Here,* the dual examination may quickly reveal the true status of the cardiovascular condition if one is present. The calculated risk is *negligible*

ADMINISTRATION OF THE EXERCISE TOLERANCE TESTS

A number of exercise tests have been employed by various investigators. Wolffe's handwheel ergometer, Parsonnet's bicyclometer, and Karpovich's treadmill have all proved useful in technically controlled studies of the physiology of exercise. Such equipment is generally too complicated for ordinary clinical use, moreover, the data provided by their use are beyond the scope of office practice. Biochemical studies and gas analysis during the exercise tests have supplied the basic data upon which simpler methods have been developed. The tendency to use the stair-climbing procedure has gained wide acceptance in recent years; this section is based chiefly upon the step test.

All exercise tests are calculated in foot-pounds of work performed; in the *stair-climbing test,* the patient's weight is multiplied by the number of feet of elevation attained. Thus a 150-lb man climbing to a height of 10 ft performs 1,500 ft-lb of work within a given unit of time Any measured flight of stairs may be employed; the portable 2- or 3-step apparatus can be used, provided certain precautions are taken. In the absence of handrails, patients with bifocal lenses *may have a tendency*

Systolic pressure	160
Diastolic pressure	88
Pulse rate	96
	344

$$\text{or } \frac{177}{344} = 0.515$$

The loss here is 0.237, which is a drop of 31 per cent from the resting index; in normal subjects the loss should not be greater than 15 per cent. In well-trained athletes there may be a post-exercise rise in the score, which is said to be due to the physiological phenomenon of "second wind."

The *CP index* is very responsive to exercise since the pulmonary data have a tendency to decrease while the cardiac figures increase; this mathematical inversion reduces the scoring level. In patients with cardiovascular disability this normal response is enhanced so that the test becomes more sensitive as functional capacity decreases. It becomes possible, therefore, to measure small changes in the clinical areas where the test is the most valuable. The resting CP index can also be utilized as a yardstick for judging day-to-day progress in the therapeutic management of heart disease, the index will reveal changes in functional capacity which may precede objective findings by many days.

After the standard 5-min rest period, the test is again repeated. The index returns to the original level in normal subjects, it may be higher in athletes Failure to return to within 5 per cent of the first score is evidence of decreasing functional capacity There is no relationship between the drop in the index and the rate of return to the preexercise level. A 30 per cent loss after exercise with a return to "normal" within 5 min, for example, may be considered a more favorable response than a 20 per cent drop which still showed a 7 per cent loss after the 5-min resting period Correlation studies indicate that restoration rate may be more important from the point of view of prognosis than the actual loss of functional capacity after effort which carries a greater diagnostic importance.

Other investigators believe that the pulmonary data alone may be used in the measurement of functional capacity of the cardiovascular system. The H-O index has thus been modified in a number of ways; the most important of these is the *gross respiratory index* Here, the vital capacity and breathholding time are mathematically added together; the test has been used as a measure of dyspnea, and, since dyspnea may be an important factor in functional capacity, the test is of value in the exercise test.

The gross tables show that: athletes score from 130 to 160; normal individuals, from 70 to 130, cardiac patients with slight dyspnea, from 60 to 70; and those with dyspnea at rest, from 30 to 60.

In the case presented previously, the respiratory index (RI) was 93 at rest and 55 after exercise, the loss was thus 38 or 41 per cent In athletes, there may be no change or even an increase, normal subjects lose up to 15 per cent. A loss of 41 per cent can be considered excessive. After the 5-min rest period, normal individuals show a complete restoration of the original RI; some may have a higher score. Delay in the return to "normal" has the same clinical implications as in the CP index.

Since the *respiratory index* contains but 2 of the 7 clinical findings of the *cardiopulmonary index*, it may be regarded as a simple screening test, which is more valuable as a measurement of the pulmonary factors after exercise than in the resting state; it is incomplete, of course, insofar as the cardiac phase is concerned.

In conclusion, it must be emphasized that all function tests requiring patient cooperation suffer from the common denomination of motivation This is particularly true of pulmonary data where the subject alone has control of the procedure *Vital-capacity, breathholding*, and *pressure-breathing data* are only of value if the individual offers his best performance This is recognized by all research groups in this field and many authors have pointed out that this is the principal reason why athletes' scores are likely to be higher and patients' scores lower. Athletes always strive to give their best performance, patients may have a variety of reasons for keeping low scores The experienced examiner will quickly detect malingering

EXERCISE AND THE ELECTROCARDIOGRAM

Perhaps the most widely used exercise-tolerance test currently employed is concerned with the electrocardiographic changes which develop after physical stress. The best-known of these procedures is the *Master 2-step test*, in which the patient makes a given number of

ascents over a suitable type of portable stairs. Tables based upon weight and age determine the degree of work performance. In certain instances a *double 2-step Master test* is indicated. Because exercise may produce a relative hypoxia in heart muscle as the result of a poorly functioning coronary circulation, disturbances in electrolyte metabolism may occur which are reflected in the electrodynamic pattern of the myocardium; changes in the depolarization, repolarization, and conducting mechanisms can develop The most frequent finding is in relation to the *S-T segments* and T waves; these show a drop in amplitude or a change in polarity with depression of the S-T segments and inversion of the T waves. On the other hand, T waves, which are "normally" isoelectric or inverted, may become upright.

The validity of the test as a measure of functional coronary insufficiency is still a subject of considerable debate among research groups, other factors in addition to the hypoxial syndrome produced by exercise may be *responsible for similar* electrocardiographic alterations. *Emotional reactions* and *psychosomatic stress* while performing the test have been shown to cause marked T-wave changes. *Orthostatic factors* may likewise play a part in the development of these electrodynamic alterations.

In well-controlled performances of the test and with the elimination of other provocative stimuli, the exercise electrocardiogram may, however, yield important clinical information not obtained by any other diagnostic method A *change in the polarity of the T waves* or the development of *S-T segmental depressions,* when associated with other evidence of coronary-myocardial disease, may have significant prognostic implications. When other clinical signs are doubtful in any given case of suspected heart disease, the test serves as confirmatory evidence.

Other electrocardiographic abnormalities are also noted after the exercise test; *delay in intraventricular conduction* or *lengthening of the Q-T interval* are suggestive of coronary insufficiency Irregularities of rhythm are common, most of them are premature beats The clinical significance of postexercise *extrasystoles* is not well understood, some authors believe that no special importance attaches to their development Others consider the extrasystoles to be of significance in relation to the T wave of the next normal beat following the premature beat; it has been postulated that if this T wave changes configuration or becomes inverted, this change indicates coronary insufficiency. *Atrial fibrillation* or *flutter* has been found after the effort test; *heart block* has also been noted.

An important part of the electrocardiographic test, which is frequently neglected, is concerned with the *5-min postexercise tracings*, here a number of changes may occur, particularly in regard to the T wave In certain instances, where there has been *no alteration* directly after the test, abnormalities develop within the 5-min rest period

Abnormalities which are produced by the test ordinarily disappear within 5 min; however, such changes *may persist* for as long as 15 or even 30 min. There have been reports of such alterations lasting for several days without clinical evidence of myocardial infarction, although the presumption is that a relatively small lesion, possibly subendocardial, has occurred. Some clinicians regard the test as incomplete unless a *follow-up record* is made on the following day, this is important in those patients where marked abnormalities were noted after the test.

EXERCISE AND THE ARTERIOGRAM

The hemodynamic phenomena of the cardiac cycle are easily investigated by a simple pulse-wave recorder. Technically, an arteriogram is easier to record than an electrocardiogram Most *multichannel electronic* electrocardiographs, as well as the photographic string-type apparatus permit simultaneous registration of both the pulse and the ECG. A number of pulse-wave recorders are now available, they extend from the glycerin capsule pressure device to the accurate *strain-gage* transducers. For ordinary clinical use, the pneumatic transmission type of recorder produces satisfactory tracings; it is easy to operate and requires a minimum of adjustment. Simplicity of use is an *important* factor in securing postexercise records when split seconds count

It is strange that, although the polygraph was developed and was widely used before the clinical electrocardiograph, polygraphic technique has lagged behind the pace set by electrocardiographic methods of cardiovascu-

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Perhaps the most widely used exercise-tolerance test currently employed is concerned with the electrocardiographic changes which develop after physical stress. The best-known of these procedures is the *Master 2-step test*, in which the patient makes a given number of

slope of the arteriogram; the most important of these are the peripheral pressure-resistance vectors of the general circulation. The peripheral resistance is reflected in the rebound delay indicated by the D-E stroke. When resistance is low, the notch appears at a lower point *in the C-F slope than* when resistance is high. Athletes, as a group, show a low point D compared with patients suffering from certain types of *hypertension*, where the *notch* is high.

In order to simplify description of the position of the dicrotic *notch for* clinical use, Opitz and the author suggested the use of a *dicrotic index*; this expresses the ratio between the maximum vertical *height of the B-C* projection and the vertical height of the lowest dip of the notch measured from the base line (Fig. 3-57C). In most normal individuals, the dicrotic index averages about 50 per cent, as indicated above, the index is low in athletes and may drop to 25 to 30 per cent. In cardiovascular disease of various types, the index may be as high as 55 per cent

Studies of the dicrotic index have shown that, in the normal heart, the index may vary from beat to beat, In addition to a respiratory factor, *there are many neurogenic effects* which are constantly changing the mechanism of peripheral resistance These alterations in the index, which range from 2 to 6 per cent, are suggestive of a *labile and normally* responsive peripheral vascular circulation. When the index is constant and shows very slight or no variations (0 5 to 1 per cent), the clinical implication is concerned with a *functional or pathological* loss *of autonomic control.*

After the exercise test, the dicrotic index falls *in normal subjects, the* drop is usually in the range of 10 to 20 per cent *Thus, if the resting* index was 54 per cent, the postexercise levels may be from 34 to 44 per cent. On the other hand, in certain cardiovascular conditions, the index may rise from 5 to 15 per cent after the test. Ordinarily, *the dicrotic index returns* to the preexercise level within the 5-min rest period but it may be delayed in patients with coronary disease.

In *aortic valvular insufficiency* and *in a number* of general noncardiovascular diseases, the dicrotic notch may be very low or even 0.

The changes which occur in the resting and exercise arteriogram just described are alterations which take place within a single cardiac cycle *Changes in rhythm* also occur and may have considerable clinical *importance. The* most significant of them is the *development* of *pulsus alternans* after effort. Pulsus alternans has been recognized for over 85 years and it has traditionally carried a serious *prognosis* although more recent studies have modified its usual sinister significance. This interesting change is dramatically demonstrated *in the* arteriogram with its alternating larger and smaller beats.

Pulsus alternans, when it develops after the exercise test, has definitive clinical significance. *Pseudopulsus* alternans of the sinus or nodal type may also be suggestive of functional incapacity when considered with other abnormalities *developing after effort.* Extrasystolic pseudopulsus alternans may be important in relation to the T-wave changes which occur in the normal beat following the ectopic beat.

Of especial interest is *alternans of the dicrotic notch*, described by *Groedel* Two types have been noted, In one, there is no change in the height of the B-C projection but the dicrotic index becomes alternately higher and lower. This is a specific arteriographic alteration not seen by any other method, ballistocardiographic studies have not revealed correlating factors. From the available evidence, it is doubtful that peripheral phenomena are responsible for the alternation, it is more *likely* that the finding is cardiac in origin, It is believed that the condition may be a precursor of true pulsus alternans and, as such, *should* have *the* same prognostic importance. Present studies give *support to this concept.*

EXERCISE AND HEART SIZE

Determination of heart size by roentgenray examination has long been an important part of cardiovascular study. The heart *readily* lends itself to x-ray visualization since it is surrounded by normal contrast media; the air *within the pulmonary fields* permits the cardiac shadow to stand out with sharp contours. Small changes in size, shape, and position of the entire heart, as well as of the individual chambers or great vessels, are easily *noted. The cardiac shadow is always examined in deep inspiration* in accordance with the standard *method of taking chest films; this* naturally increases the air volume within the lungs and enhances contrast effect. The apex is usually *clearly defined* in most subjects, but the lower or caudal margin of the heart merges with the normal subdiaphragmatic density and *may not* be seen unless there is a large gas bubble in the stomach. This contrast *may be* increased by the drinking *of* a carbonated beverage or by the standard Seidlitz powder method. The lowest *visualized point* of the right border may be connected with the lowest point of the left

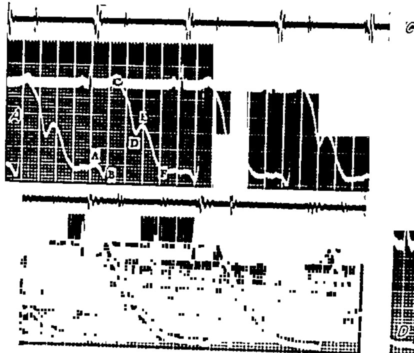


Fig. 3-57. A. Simultaneous recording of heart sounds, electrocardiogram, and radial arteriogram to show time relationship. Note that the C wave occurs at the end of the T wave but before the 2d sound. The D wave occurs after the 2d sound. B. Similar tracings. Arrow points to small wave which developed on the B-C stroke after the exercise test. C. High dicrotic index from hypertensive patient Height of B-C stroke is 25 mm, height from base line to base of D wave is 17 mm; dicrotic index is thus 68 per cent. D. Low dicrotic index from athlete. Height of B-C is 31 mm, D wave is 8 mm; dicrotic index is thus 26 per cent.

lar investigation. This has been unfortunate for it has long been recognized that the hemodynamic aspects of the cardiac cycle may be just as important as the electrodynamic. The arteriogram produces objective data about the heart and vascular system which are *not* shown by the electrocardiogram.

As the arteriogram is not too well known, it may be well to review some of the important features of this older method

The normal arteriogram taken from the radial pulse (Fig. 3-57A) shows a small upright wave preceding the main upstroke, this A wave is said to be due to atrial contraction but is not seen in all normal tracings [1]

The A wave is of course absent in atrial fibrillation and flutter, as well as in complete heart block and when the P-R interval is prolonged beyond 0.20 sec. It may disappear after the exercise test or it may become larger The significance of the A wave is not well understood but, in tight mitral stenosis, it usually becomes larger after the test

The main upstroke or B-C projection represents the outflow pressure gradient from the time of opening of the aortic valves at the beginning of systole to the instant when maximum systolic pressure is developed Phonovascular records show that it is this point in the arterial pulsation which is heard first when blood pressure is taken by the auscultatory method. The B-C projection is normally a straight line, after exercise, one or more small deflections may be noted (Fig. 3-57B). These small waves may have some significance.

The pressure-gradient curve during ventricular contraction is continuous, when the heart muscle has been damaged by disease and when orderly contraction is interrupted by segments of the myocardium which tend to lag, there will be irregularities in the B-C projection Such deflections thus carry the implication of functional ventricular insufficiency, when they are found after the exercise test, the discovery vies in importance with changes in the postexercise electrocardiogram Correlation studies have not, however, shown significant parallelism in the two methods; S-T and T-wave alterations may occur without associated B-C projection defects and vice versa.

The dicrotic notch (point D) is perhaps the best known and least understood part of the arteriogram, the physiological phenomena responsible for its development are still under intensive investigation. A number of factors are apparently concerned in its appearance on the C-F recession

[1] The nomenclature used was adopted by the Valley Forge Heart Institute and Research Center (1953). The letters A, B, C, D, E, and F are used for designation of specific waves or points on the arteriogram.

in size after effort than the normal heart. Therefore, the exercise-tolerance test lends itself to the profitable determination of heart size estimated by x-ray examination.

In administering the test, the same procedure for work performance employed previously is used here Any changes in the size of the resting heart after the Valsalva maneuver are noted. The resting heart is then x-rayed or an orthodiagram is made The three-dimensional size of the heart is calculated, although the surface-area measurements have some value, they are subject to the error of changes in lateral diameter. For example, the surface area may remain unaltered but the lateral diameter may decrease or increase, or the changes in the surface area may be neutralized by opposite changes in the lateral diameter

There must be no delay in reexamining the heart after the exercise test, many changes disappear after the first 90 sec, although the more diseased hearts tend to keep the enlargement longer

Occasionally, there may be an enlargement of 40 per cent over the size measured at rest.

Reduction in heart size occurs in some normal subjects and in most athletes, this reduction is rarely more than 15 per cent, with the general average about 6 per cent Nearly all individuals show some change in heart size after the test

Reexamination of the heart after the 5-min rest period is just as important as after the electrocardiographic test Most patients show a return to the preexercise size but there may be a delay in the more advanced types of cardiac disability An interesting phenomenon occurs in certain well-conditioned hearts of athletes in that the "5-min heart" may be smaller than when measured directly after exercise Various physiological explanations have been offered for this finding

Changes which take place in heart size as a result of the exercise test can be demonstrated graphically by the Bertash method the cardiac silhouette (cardiomoulage) is cut out from either the teleroentgenogram or orthodiagraphic tracing and placed in the proper anatomical position on the patient's chest, he is then photographed in front of the Alsahy international biometric grid Changes in heart size are indicated on the silhouette as well as on the graphic representation of the lateral diameter

X-ray examination of the heart after the exercise-tolerance test may sometimes reveal unsuspected old myocardial infarcts Local aneurysmal dilatation of the heart wall with its paradoxical pulsation phenomena is a well-recognized fluoroscopic and kymographic finding in healed infarcted areas of the left ventricle. Identification of such old infarcted areas may be made by the exercise test many months or even years before they are recognized by ordinary x-ray examination.

Another important postexercise observation is concerned with changes which may occur in the aorta The author has noted enlargement and dilatation of the third portion of the arch in certain patients who have been under treatment for the anginal syndrome. In these patients, the pain syndrome followed the usual pattern in that it developed after effort but the radiation phenomena were more localized to the neck and the posterior part of the chest rather than to the left shoulder and arm. The pain did not respond to nitroglycerin or other dilator drugs. This type of precordial pain was known to older clinicians as the "aortic" type in contrast to the "coronary" type. It can be due to luetic aortitis or aortic atheromatosis. As a differential diagnostic procedure, the x-ray examination may be of considerable value.

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The ballistocardiogram lends itself to the exercise-tolerance tests, tracings may be made before, directly after the test, and after the 5-min rest period The same procedures performed in the electrocardiographic and x-ray methods can be followed here The ballistocardiogram may supply information not made available by any other examination and, as such, it occupies a definitive place in the estimation of functional capacity.

In the experience of the author, while the ballistocardiograph occupies a supplementary role, it has a distinct place in the exercise-tolerance test Disturbances in the normal pattern of the tracing as the result of the loss of functional capacity may sometimes be noted when all of the other tests are negative or equivocal This has been recognized in the study of Class 3 patients where follow-up investigation has subsequently shown objective cardiovascular disability; in a number of instances, the postexercise ballistocardiogram has shown changes which have antedated by 6 to 14 months similar functional alterations as shown by other tests.

border by a symmetrical line in order to estimate surface area. In the lateral positions, a *barium swallow may be useful in determining* the posterior point of the third diameter of the heart.

Accuracy in heart size determination requires a special technique to eliminate the distance-magnification principle of transmitted light rays; the use of parallel x-rays permits an estimation of the cardiac diameters which is sufficiently reliable for clinical application Two procedures are currently employed for this purpose, *the 2-m film* gives *objective visualization of the heart and great vessels* but, because of the great distance from the target focus, the borders of the shadows tend to be fuzzy and indistinct This may make accurate mensuration difficult. Unless a special timing device is provided, the actual phase of the cardiac cycle photographed may not be known; heart size and contour may change considerably in systole and diastole

Orthodiagraphic x-ray tracings, however, are limited by many subjective factors; the chief of them are the skill and experience of the examiner In the hands of a well-trained observer, however, the method has many advantages over the 2-m film or teleoroentgenogram Fluoroscopy permits a *more detailed examination of the movements and* pulsations of the heart and great vessels, the exact time in the cardiac cycle is known The method is simple and relatively less expensive

Some of the above-mentioned disadvantages of the 2-m films are overcome by the use of roentgen kymography which permits a more leisurely examination of the cardiac movements than may be afforded by fluoroscopy.

The important measurements of heart size are *the transverse diameter* and *the width of the aorta,* in the frontal plane, *the surface area of the heart,* determined by *the long* and *broad diameters,* and *the total volume* of the heart *calculated from the surface area and the lateral diameter* Here the standard tables of Hodges and Eyster and Ungerleider and Clark, as well as a number of other works, provide comparative data based upon age, height, weight, and sex.

The *cardiac-body index,* which is the ratio between the surface area of the heart and the surface area of the body estimated from the Dubois charts, is perhaps the most accurate method of comparing the heart size of a given individual with that of his statistical group. The traditional *cardiothoracic ratio,* which expresses the relation of the width of the heart to the width of the thorax, has been generally discarded because it is unreliable.

While it is recognized that the "normal heart size" has as many variations as the "normal electrocardiogram," these measurements are of extreme importance when used in studying the same heart *at rest and after exercise. Inherent errors of the* method may invalidate the absolute size of a given heart but will have no appreciable effect in the clinical evaluation of changes which may take place under stress.

It has long been known that the normal *heart may show considerable* change in size following certain physiological stimulation During the performance of the Valsalva maneuver, for example, the normal heart becomes smaller; in athletes, there may be a decrease in total heart size, calculated by the three-dimensional method, of 15 to 20 per cent. The responsiveness of the heart to this procedure is apparently quickly lost with the onset of functional insufficiency; it is also decreased with advancing age. Studies of Michaelson have shown interesting correlations between loss of sinus arrhythmia and the loss of the Valsalva effect on heart size, it can sometimes be predicted that the heart will not become smaller in individuals of the age groups during which sinus arrhythmia disappears. *In the groups of individuals aged 35 years and more, the Valsalva test may be of value in the determination of functional capacity.*

After the standard exercise test, normal subjects show a slight to moderate loss in the Valsalva effect, heart size may decrease only from 4 to 8 per cent compared to perhaps 10 to 15 per cent before the test. In patients with functional insufficiency, the heart may show no change, or there may be an increase in size *After the 5-min rest period,* the Valsalva effect usually returns.

It has been established that the well-conditioned heart of athletes has a tendency to become smaller during exercise; this applies *both* to those hearts which show some intrinsic enlargement as the result of sports activities and *to those which are normal or smaller* than normal This finding stands in marked contrast to the enlargement which takes place after exercise when cardiovascular disability is present It has been shown that physical fitness may decrease the degree of the enlargement, still, the diseased heart is far more likely to increase

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There must be no delay in reexamining the heart after the exercise test; many changes disappear after the first 90 sec, although the more diseased hearts tend to keep the enlargement longer. There may be remarkable changes in heart size: an increase of 10 to 25 per cent is not uncommon in patients with one of the coronary artery diseases. Occasionally, there may be an enlargement of 40 per cent over the size measured at rest.

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STATE OF THE CUTANEOUS CIRCULATION

Inspection and Palpation. Inspection and *palpation* of the extremities may frequently give information of great value regarding the local cutaneous circulation.

NUTRITIONAL CHANGES IN THE SKIN. The first step is to look for old signs of nutritional disturbances, such as healed scars or loss of a portion of a digit or digits. The texture and consistency of the skin and subcutaneous tissue also reflect the state of the cutaneous circulation For example, the absence of wrinkling over the joints of the fingers may be due to abnormal attachment of the skin to the underlying structures (scleroderma), or there may be a loss of the firmness and elasticity of the skin and subcutaneous tissues Thickening of the tips of the fingers and piling up of scaly material at the junction of the nail plate and the fleshy portion of the digit likewise indicate abnormalities of the cutaneous circulation

CUTANEOUS TEMPERATURE. Palpation of the skin is also of value in the gross determination of cutaneous temperature For this procedure to have any significance, however, it must be carried out some time after the patient has entered the examining room and removed his shoes and stockings, in order to permit time for the establishment of an equilibrium between the environmental and the cutaneous temperature The finding of *coldness* of a digit or digits, or of an entire foot, may indicate an impaired local cutaneous blood flow Whether this is on the basis of vasospasm or of structural changes in the blood vessels can be determined only by repeating the observations after removal of vasomotor tonus (see below).

STATE OF SWEAT GLANDS. Palpation will also reveal whether or not there is an alteration in the normal sweating mechanism *Hyperhidrosis* may be a manifestation of increased vasomotor tone, while *anhidrosis* may result from a local impairment of blood flow to the sweat glands. The latter response also follows complete sympathetic denervation of an extremity or destruction of a peripheral mixed nerve

STATE OF NAILS In the presence of arterial insufficiency, the nails grow more slowly and show certain changes, such as deformity, brittleness, and pigmentation. At the same time, there may be an increase in the thickness of the nails and the appearance of parallel ridging.

HAIR GROWTH. Another sign of impaired circulation is a reduction or absence of the growth of hair on the toes. However, it is necessary to point out that, for these changes to appear, a considerable degree of ischemia must be present.

POSTURAL COLOR CHANGES. Valuable information regarding the state of the cutaneous circulation can be obtained by studying the color changes of the skin produced in the extremities by altering their position. Before performing this test, however, it is advisable to have the limbs exposed to a comfortable environmental temperature (74°F) for approximately one-half hour.

Horizontal Position. The first step is to examine the extremities with the patient in the supine position. Under these circumstances, the normal hand or foot should demonstrate a slight pink color. The presence of pallor, cyanosis, or rubor is generally interpreted as indicating the existence of some abnormality of the local vascular bed. This is especially true when the change is noted in one limb or one or several digits. It is necessary to point out, however, that such findings have significance only if various systemic conditions which cause alterations in skin color can be eliminated as possible causative factors. Among them are shock, heart failure, the cyanotic type of congenital heart disease, processes in the lungs which interfere with oxygenation of the blood, blood dyscrasias, and carbon monoxide poisoning

Elevated Position. The next step is to elevate the extremities and maintain them in this position for some time by supporting them. If a pallor appears over the distal portion of the limbs, it is good evidence that a reduced arterial circulation exists. If the normal pink color persists, the patient is asked to flex his feet repeatedly, or, in the case of the upper extremity, to open and close his fists, while keeping the limbs in the elevated position. Then they are brought down to the level of the examiner's eyes and again inspected for color changes The importance of this step is that it may bring out a pallor of the distal portions of the extremities which was not no-

Since the ballistocardiogram is chiefly a record of the expulsive forces of the heart and of the recoil movements of the body, changes in various pressure gradients, secondary to exercise, can be determined. Decrease in vigor of ventricular contraction tends to decrease the *amplitude of the I-J stroke which thus can be* utilized as an approximate measure of functional capacity. In *athletes,* this stroke may be large, in patients with *coronary insufficiency,* it is small.

*After the exercise test, the I-J stroke may be*come larger or remain unchanged in normal subjects, in those with coronary insufficiency, it becomes smaller and may show defects. The two component waves may show different responsive alterations, the I wave usually decreases more in *depth than the J wave in height. The author* believes that the decrease in the I wave carries more clinical significance than the drop in the J wave On the other hand, the J wave may show more postexercise distortions than the I wave.

The J-K stroke is normally of greater amplitude *than I-J, the K wave is deeper than the I wave.* After exercise, this relationship may be reversed if coronary insufficiency is present, the K wave may become very small. Slurring of the J-K stroke may involve the K wave in an abnormal pattern. Changing peripheral resistance may cause altera*tions in the K wave*

Other abnormalities may occur in the individual waves alone or in multiple defects, in this connection, emphasis must be placed on *Starr's* rule no abnormality that is not regularly repeated is worthy of attention.

The H wave deserves special attention, it may increase in amplitude after exercise; it is usually high in myocardial infarction. When the H and J waves are nearly equal in height, an M-shaped pattern is recognized, deep notching of the J wave produces a late M-shaped pattern

The diastolic waves, L, M, N, and sometimes O, are not understood as well, the author has not found isolated changes in these. When alterations occur, they are associated with major abnormalities in the larger complexes.

As in the electrocardiogram, the *normal subject* shows very little or no change in the exercise ballistocardiogram; in certain responsive individuals who develop a tachycardia after the test, there may be alterations in the K wave The development of abnormal patterns sug*gests functional insufficiency.* The author has not been able to correlate specific changes in the various components of the tracing with definitive degrees of disability. On the other hand, there is a marked correlation between the four degrees of abnormality designated in the classification of Brown and the results obtained by the other functional tests Correlation studies between the ballistocardiogram and the electrocardiogram have been made by several authors; while the reports represent different experiences, there is considerable agreement in the results of both methods when used in moderately advanced and advanced cases of coronary disease. Critical evaluation of the preclinical and early manifestations of the disease will require continued investigation by many observers.

Through the use of these five procedures, the heart at work can be objectively evaluated Any one procedure alone may be productive of information not previously disclosed by examination of the cardiovascular system at rest; performance of all of the tests, while not indicated in every case, will provide data of inestimable value. The apparatus necessary for giving these tests are available to nearly all *clinicians, they are the basic tools of modern* medical practice. The extended time factor in performing the function tests is recognized but this is offset in many ways, if the physician is able to supplement experience and judgment with a factual score card having an important bearing upon the future activities and the very life of his patient, both will have been well served by the determination of functional capacity.

THE ARTERIAL CIRCULATION

Impairment of the arterial system in the extremities can in most instances be readily recognized by the use of simple tests, capable of being given either at the bedside or in the office, and requiring *no special apparatus other* than an oscillometer Through their application, it is possible to evaluate the state of the cutaneous circulation, the degree of involvement of the main arteries, and the influence of vasospasm on the local blood flow Since each test gives information of a specific nature, it is *necessary to utilize all of them in order to* obtain a comprehensive evaluation of the state of the vascular system.

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STATE OF SWEAT GLANDS Palpation will also reveal whether or not there is an alteration in the normal sweating mechanism *Hyperhidrosis* may be a manifestation of increased vasomotor tone, while *anhidrosis* may result from a local impairment of blood flow to the sweat glands The latter response also follows complete sympathetic denervation of an extremity or destruction of a peripheral mixed nerve

STATE OF NAILS In the presence of arterial insufficiency, the nails grow more slowly and show certain changes, such as deformity, brittleness, and pigmentation. At the same time, there may be an increase in the thickness of the nails and the appearance of parallel ridging.

HAIR GROWTH. Another sign of impaired circulation is a reduction or absence of the growth of hair on the toes. However, it is necessary to point out that, for these changes to appear, a considerable degree of ischemia must be present

POSTURAL COLOR CHANGES. Valuable information regarding the state of the cutaneous circulation can be obtained by studying the color changes of the skin produced in the extremities by altering their position. Before performing this test, however, it is advisable to have the limbs exposed to a comfortable environmental temperature (74°F) for approximately one-half hour.

Horizontal Position. The first step is to examine the extremities with the patient in the supine position. Under these circumstances, the normal hand or foot should demonstrate a slight pink color. The presence of pallor, cyanosis, or rubor is generally interpreted as indicating the existence of some abnormality of the local vascular bed This is especially true when the change is noted in one limb or one or several digits. It is necessary to point out, however, that such findings have significance only if various systemic conditions which cause alterations in skin color can be eliminated as possible causative factors. Among them are shock, heart failure, the cyanotic type of congenital heart disease, processes in the lungs which interfere with oxygenation of the blood, blood dyscrasias, and carbon monoxide poisoning.

Elevated Position The next step is to elevate the extremities and maintain them in this position for some time by supporting them If a pallor appears over the distal portion of the limbs, it is good evidence that a reduced arterial circulation exists If the normal pink color persists, the patient is asked to flex his feet repeatedly, or, in the case of the upper extremity, to open and close his fists, while keeping the limbs in the elevated position Then they are brought down to the level of the examiner's eyes and again inspected for color changes The importance of this step is that it may bring out a pallor of the distal portions of the extremities which was not no-

ticed with merely maintaining them in the elevated position. Such a response in the case of the lower extremity is called a *positive plantar pallor test* (Samuels) and indicates the existence of reduced arterial circulation to at least the foot. A similar interpretation can be made in the case of pallor of the palmar surface of the hand

Dependent Position. Finally, the extremity, which has been maintained in the elevated position, is now placed in dependency. Normally, a pink color will return within 10 sec or less (time of return of color in dependency). In the presence of an impaired arterial circulation, however, there will be a definite delay to as long as 45 to 60 sec or more. Furthermore, when the normal color does appear, it will be irregular and patchy rather than uniform.

Coincident with the skin color change, the superficial veins on the dorsum of the foot will fill with blood (*venous filling time*) The response should also occur within 10 sec after the extremity is placed in dependency A delay beyond this time has the same significance as a delay in the return of color [2] It is of interest that the extremity which manifests a slow reappearance of color will generally demonstrate an intense cyanotic rubor if it remains in dependency for any period of time Such a change indicates that the tone of the superficial vessels is low or absent and that, as a result, there is pooling of blood in the subpapillary venous plexus.

Subpapillary Venous Plexus Filling Time. In order to obtain information regarding the state of tonus in the minute vessels of the skin, the following simple test can be performed. digital pressure is applied to the skin for several seconds and then the color changes are observed immediately after the force is removed A normal response consists of, first, the momentary appearance of pallor of the skin, as a result of displacement of blood from the subpapillary venous plexus into the surrounding and deeper tissues, followed by a return of normal pink color within a second or two (*subpapillary venous plexus filling time*) In the presence of a reduction in tone of the small vessels of the skin, there is a delay in the reappearance of the normal color, as long as 4 to 5 sec. At the same time, the pale area will fill irregularly. Excessive vasospasm or organic changes in the arterial tree evoke the same type of response.

The subpapillary venous plexus filling time is also of value in differentiating between living and nonliving tissues. In the presence of an irreversible color change resembling cyanosis, the application of digital pressure has no effect; such a response indicates that the area involved will eventually develop superficial or deep gangrene. On the other hand, in the case of reversible cyanosis, pressure to the area will momentarily cause the disappearance of the color change, with immediate return after removal of the force.

Histamine Wheal Test. When a small quantity of histamine is injected intracutaneously, a triple response occurs, the final change being the appearance of a *wheal.* Since it has been shown that the speed with which the latter forms is dependent solely upon the rate of cutaneous blood flow, the procedure has been applied to the problem of evaluating the state of local circulation It is performed as follows:

> With the extremity in the horizontal position, about 0.1 ml of a 1:1,000 solution of histamine acid phosphate is injected intracutaneously at various levels on the extremity The areas are then examined for the appearance of a wheal. Normally, this type of response occurs within 3 to 5 min after injection of the drug. A delay beyond this point indicates the existence of some impairment of cutaneous circulation. Lack of formation of a wheal can be interpreted as signifying the presence of a precarious blood supply.

The histamine wheal test is of value in ascertaining whether or not impending gangrene exists, and in determining the proper site for amputation of a limb It is also helpful in following the rate of progression of the pathological process in the arterial tree. However, it must be emphasized that the procedure is useful only in evaluating the state of the cutaneous circulation and gives no information regarding muscle blood flow.

TESTS FOR DETERMINING THE STATE OF PRINCIPAL ARTERIES

Examination of Peripheral Blood Vessels. Of prime importance in determining the state of

[2] It is necessary to point out that, in the presence of varicosities, neither this test nor the time of return of color in dependency is valid, since the skin color will return and the veins will fill as a result of retrograde flow of blood, rather than through the normal pathway involving arterial, capillary, and venous channels

the peripheral circulation is palpation of the principal arteries of the extremities. However, it is necessary to point out that changes in the amplitude of pulsations are not always due to local abnormalities of these vessels (see below).

SYSTEMIC CONDITIONS ALTERING PULSATIONS. Certain systemic disorders affecting the heart and peripheral circulation, such as the terminal stage of heart failure, paroxysmal tachycardia, and shock, may cause marked reduction in the peripheral pulses or even their complete disappearance. *Aortic stenosis*, constrictive pericarditis, pericardial effusion with tamponade, and myocarditis, may have a similar effect. In atrial fibrillation, the state of the peripheral pulsations is difficult to determine because of wide variations in amplitude. In aortic insufficiency, the pulses are exaggerated and bounding.

AORTA AND ITS BRANCHES: OBSTRUCTION OR EXTRINSIC PRESSURE. Involvement of the great vessels and their main branches proximal to the extremities is the cause of changes in the peripheral pulsations. Such a situation exists in coarctation of the aorta, thrombosis of the aortic bifurcation (*Leriche syndrome*), and dissecting aneurysm of the abdominal or thoracic aorta. Extrinsic pressure on any of the main arteries in their course through the chest or abdomen, as by tumors or other masses, will produce a similar type of alteration.

CHANGES IN LOCAL NONVASCULAR TISSUES. Besides the above-mentioned conditions, the pulsations in the peripheral vessels may be affected by changes in the overlying tissues. Among them are induration and thickening of the skin, pitting and nonpitting edema, an increase in subcutaneous fat, and local hypertrophy of the musculature.

LOCAL CHANGES IN VESSELS. When the above-mentioned conditions have been eliminated as possible causative factors, then alterations in the pulsations of the arteries in the extremities can be attributed to local changes in the vessels themselves. Reduced pulsations may be due to marked vasospasm or to permanent structural abnormalities in the vessel wall, as occurs in thromboangiitis obliterans and arteriosclerosis obliterans. Removal of normal or exaggerated sympathetic control (through sympathectomy or the use of sympathetic blocking agents) produces an increase in the amplitude of the pulsations as a result of passive dilatation of the arteries. A marked vasodilator response, as is observed in *erythromelalgia*, causes a similar type of change.

Technique of Examination. For a proper study of the pulses, it is necessary for the observer to be comfortable, since the assumption of an awkward position places a strain on the muscles of his body, thus dulling his perceptive senses. It must also be pointed out that, when too firm pressure is applied in feeling for the vessel, the pulse in the finger of the examiner may be mistaken for the one in the artery of the patient. Furthermore, a reduced pulsation under these circumstances may not be felt by the examiner. It is, therefore, essential to vary the pressure on the vessel in each instance. If the artery is located some distance below the skin, a greater degree of force is necessary.

EXAMINATIONS OF PULSATIONS IN UPPER EXTREMITY. In the upper extremity, the pulsations of the brachial artery can be readily palpated by compressing the vessel against the humerus at about the level of the lower third of the arm (Fig. 3-58A). The radial artery is felt in its usual position at the wrist. The ulnar artery can be palpated at the same level at the wrist, but on the opposite side (Fig. 3-58B). It is generally situated more deeply and requires firm pressure in order to locate its position.

If the vessel *cannot* be felt, the following procedure should be performed (ulnar confirmatory test). The extremity under examination is elevated, in order to allow for drainage of blood out of the small vessels of the skin, and then the radial artery is obliterated at the wrist by firm digital pressure. After this, the subject opens and closes his fist a number of times in order to facilitate further venous drainage out of the hand. With the pressure at the wrist maintained, the hand is brought down to the level of the heart and the fist is opened, although the fingers are not fully extended. The return of color to the fingers and palm is then studied. If the ulnar artery is patent, there will be immediate flushing of the skin as a result of blood entering the superficial and deep volar arches from this vessel. If the ulnar artery is occluded, the palmar surface of the hand will remain pale as long as the pressure is maintained on the radial artery, while removal of the compression should immediately cause a return of color.

This type of response indicates that either the ulnar artery is occluded by some type of pathological process or an anatomic anomaly exists in the connection between this vessel and the volar arches.

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... since it has been reported to occur in approximately 13 per cent of people (Silverman)

OSCILLOMETRY

The value of oscillometry as a diagnostic tool in vascular diseases is still a moot question. There are some workers (*Allen et al.*) who believe that the procedure gives little information of value, while others (Atlas, Rinzler et al.) consider it a very important part of a vascular examination. On the basis of available clinical evidence and personal experience, it would appear that the latter view should be supported, provided the limitations of oscillometry are recognized.

Technique. Several rather inexpensive and satisfactory oscillometers are available commercially. However, in order to compare findings obtained on the same subject at different times, it is necessary to use the same apparatus each time. It is also important to have a constant environmental temperature and emotional state of the patient if reproducible results are desired. During the test, the patient should be lying on his back, avoiding any interest in the procedure.

The oscillometer consists of a modified pneumatic cuff connected to a sensitive aneroid capsule which measures the pulsatile alteration in the size of the limb with each cardiac systole. In order to observe this change on the recording instrument, the pressure in the cuff is raised to a level which is not too great to interfere with blood flowing in, but still sufficient to cause enough compression of the arm to act as a good coupling agent for the transmission of the volume change. In order to obtain optimum conditions for this purpose, the pressure in the cuff is raised to above systolic level and then lowered in steps of approximately 10 mm Hg by means of an escape valve. With each drop, the cuff is connected with the recording capsule by turning a valve arrangement, and the range of movement of the needle is recorded in arbitrary units. The important reading is the one indicating the greatest excursion of the pointer.

The cuff is generally applied at several sites on each extremity. In the lower extremity, readings are obtained at the level of the calf and the lower portion of the leg above the ankle. If the readings at the calf are reduced, then the thigh just above the knee is studied. In the upper extremity the usual sites of application of the cuff are the upper part of the forearm and the wrist and, if the readings at the forearm are low, the lower part of the arm.

RANGE OF NORMAL READINGS. One of the disadvantages of the oscillometer is the fact that there is considerable variation in the normal range for the different sites. In the lower extremity, at the thigh above the knee and at the calf, it is between 5 and 12 units or higher. For the leg above the ankle, the range is between 2 and 6 units or higher. In the upper extremity, the figures vary between 5 and 12 units or higher for the lower part of the arm and upper part of the forearm and between 1½ and 4 units or higher for the wrist. Readings which fall below the lower limit for any one site should be considered abnormal and investigated further. A significant difference in the figures for a corresponding level on two extremities generally has meaning, particularly if one measurement is high-normal or above while the other is low-normal or below.

VALUE OF METHOD. Oscillometry is helpful in obtaining a more quantitative and reproducible index of the state of the main arteries than is possible by palpation of the peripheral pulses alone. Through repeated studies at intervals, it is possible to ascertain whether or not any progress in the obliterative process has occurred. The procedure is also useful in diagnosing mild degrees of arterial impairment which cannot be determined by digital palpation of the pulsations. Oscillometry is of value in the exact localization of segmental occlusion of arteries, as a preliminary to the use of a venous or arterial transplant. Such information is also very important when embolectomy is contemplated in the treatment of sudden obstruction of a main artery by an embolus. Finally, the procedure is helpful when local changes in nonvascular tissues exist in the foot which make palpation of the vessels difficult, as in the case of obesity, thickening and induration of the skin around the ankle, and nonpitting and pitting edema. It is necessary to emphasize that the oscillometers available for clinical use are not sensitive enough to pick up oscillation in the small collateral vessels, in which the pressure is lower than in the main

EXAMINATION OF PULSATIONS IN LOWER EXTREMITY. The femoral artery can be readily felt in the groin below Poupart's ligament (Fig. 3-58C). In the case of the popliteal artery, it is necessary to place the patient on his abdomen and cross the extremity being examined over the other so as to relax the tissues in the popliteal space (Fig. 3-58D). Because the artery is located some distance below the skin, firm pressure is necessary in order to palpate it This is obtained by placing the fingers of the other hand over the examining fingers and pressing forcefully In such a manner, the perceptive sense of the palpating digits is not dulled.

In the foot, it is necessary to palpate for the dorsalis pedis and the posterior tibial arteries The dorsalis pedis artery is usually felt on the dorsum of the foot, its position with respect to bony landmarks being quite variable. Generally, however, it is some distance medial to the midline (Fig 3-58E) The posterior tibial artery is palpated behind and beneath the medial malleolus (Fig 3-58F) When the left foot is being examined for the presence of this vessel, the observer stands to the left of the patient and cups the fingers of either hand over the medial malleolus, so that the finger tips slide off the bone to enter the groove below. The opposite position is assumed when the right posterior tibial artery is being examined In each instance the nonpalpating hand is used to dorsiflex the foot slightly, so as to put the artery somewhat on stretch.

ABERRANT VESSELS. Besides palpating the normal arteries, it is necessary to search for anomalous vessels. If there is difficulty in feeling the pulsations in the radial artery, the dorsal surface of the base of the thumb should be examined for the existence of an aberrant vessel. In the lower extremity, obstruction of the popliteal artery may result in the appearance of prominent lateral or medial superior genicular arteries coursing over the knee. When the posterior tibial artery is absent, a large vessel may be found along the upper border of the lateral malleolus, which is probably an enlarged perforating branch of the peroneal artery (Fig. 3-58G).

INTERPRETATION OF ABNORMAL FINDINGS Inability to palpate the brachial, radial, femoral, popliteal, or posterior tibial arteries generally signifies the presence of either a structural vascular disorder or marked vasospasm. However, on occasion, pulsations of the posterior tibial artery cannot be felt because its position is masked by a prominent medial malleolus found in people with "squat feet." Similarly, anatomic alterations in the popliteal fossa may make the popliteal artery impossible to palpate. The absence of pulsations in the ulnar artery, established by the ulnar confirmatory test, may be of diagnostic importance for, in thromboangitis obliterans, this vessel is one of



Fig. 3-58. A. Palpation of the brachial artery pulse by compressing vessel against the humerus B. Palpation of ulnar and radial arteries C Palpation of femoral artery. D. Palpation of popliteal artery, E, of dorsalis pedis artery; F, of posterior tibial artery; G, of aberrant artery.

the first to be affected by the occlusive process. On the other hand, the absence of one or both dorsalis pedis arteries may be a normal variant, *since it has been reported to occur in approximately* 13 per cent of people (Silverman)

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Technique. Several rather *inexpensive* and satisfactory *oscillometers* are available commercially. However, in order to compare findings obtained on the same subject at different times, it is necessary *to use the* same apparatus each time It is also important to have a constant environmental temperature and emotional state of the patient *if reproducible* results are desired During the test, the patient should be lying on his back, avoiding any interest in the procedure.

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arteries. This reduces the range of clinical applicability of the apparatus, since in occlusive arterial vascular diseases the collateral circulation is generally responsible for nourishing the tissues. It also follows that, in great part, with structural impairment of the small arteries and arterioles distal to the main arterial channel, the oscillometric readings might still be within the normal range.

In summary, it can be stated that *oscillometry is of great value in the diagnosis of an occlusive arterial vascular disease, in the determination of the rate of progression of the obliterative process, and in the localization of the site of obstruction of a main vessel.* However, it is of little use, and may even be misleading, in arriving at a proper conclusion regarding prognosis.

TESTS FOR REMOVAL OF VASOMOTOR TONUS

Many of the above-mentioned tests do not differentiate between impaired circulation consequent to structural changes in the blood vessels and that which follows a temporary increase in vasomotor tone Since vasospasm is much more amenable to treatment and has a much better prognosis, it is important to determine the role of this state in the clinical picture. In order to obtain such information, vasomotor control is temporarily removed and the resulting increase in skin temperature studied The latter response is caused by the augmented cutaneous blood flow which follows passive dilatation of the skin vessels It can be assumed that the greater the rise in skin temperature produced by inhibition of sympathetic control, the more marked was the previous state of vasomotor tonus

Technique. Although a room with constant temperature is advantageous, it is not necessary for obtaining acceptable skin temperature readings Still, it is advisable to perform the studies in a room which is free of drafts and in which the temperature is within physiological limits, i.e , between 68 and 77°F With regard to the choice of a *skin thermometer*, one utilizing two sets of connected thermocouple junctions is preferable However, a much less expensive instrument which can be used is a modified mercury thermometer with a flat, widened base. Generally, a control set of readings is obtained after equilibrium with the environmental temperature has been reached; another series of readings is taken about 20 min after elimination of sympathetic control by one of the several methods mentioned below.

PROCAINE BLOCK OF PERIPHERAL NERVES. A simple way of producing temporary sympathetic denervation of the blood vessels in the extremities is by *local blocking* of the sympathetic fibers contained in the peripheral mixed nerves. In the lower extremity, partial sympathetic denervation is obtained through procaine infiltration of the posterior tibial nerve, which runs behind and below the medial malleolus in the vicinity of the posterior tibial artery. In the upper extremity, the desired effect is produced by anesthetizing the ulnar nerve at the elbow and the median nerve at the wrist.

BLOCKING OF PARAVERTEBRAL SYMPATHETIC GANGLIA OR TRUNKS. Sympathetic denervation can be accomplished by blocking of appropriate paravertebral sympathetic ganglia with procaine or a local anesthetic with more prolonged action. For the upper extremity, the 1st, 2d, and 3d thoracic ganglia are injected; for the lower extremity, the anesthetic is deposited around the 1st, 2d, and 3d lumbar ganglia. Sympathetic denervation of both lower extremities can also be produced by spinal anesthesia.

INDIRECT VASODILATATION (REFLEX VASODILATATION). Another method for the removal of sympathetic tonus consists of the application of heat to distant portions of the body in order to produce reflex vasodilatation in the limbs under study This can be accomplished by means of the application of several hot water bottles or electric pads to the axillae, abdomen, and chest, or by the use of a heat cradle, heat lamp, or diathermy apparatus. Another means consists of immersing the limbs not being studied in buckets containing water at a temperature of 113°F With each procedure, the heat is maintained for approximately one hour and the body during this period is covered with blankets

CHANGES IN SKIN TEMPERATURE PRODUCED BY REMOVAL OF VASOMOTOR TONUS. In the normal individual, sympathetic denervation is followed by a rise in skin temperature of the digits to about 86 to 95°F Approximately the same level is reached in the case of patients

with excessive sympathetic tonus, although the magnitude of the increase is much greater because the control readings are always lower than in normal individuals In the patient with an obliterative vascular disease alone, removal of vasomotor tonus generally causes a rise from approximately 75 or 77° to 80 or 82°F, but not higher. This is due to the fact that in spite of elimination of all sympathetic tonus, the normal increase in blood flow does not occur as a consequence of the structural changes in the cutaneous vessels preventing adequate dilatation. If there is an element of vasospasm superimposed on an occlusive vascular disease, the rise in temperature may be somewhat higher A drop in surface temperature of one or more toes after a successful sympathetic block has great significance, for it indicates that the procedure has produced an actual shunting of blood from the toes, in which the drop of temperature is observed, into other portions of the foot, in which the vessels are capable of dilating. This type of response is a contraindication to the use of sympathectomy as therapy, since under these circumstances permanent sympathetic denervation might be followed by the appearance of gangrene in the digits previously demonstrating the fall in temperature

TESTS FOR DETERMINING THE STATE OF THE MUSCLE CIRCULATION

Studies for evaluating muscle circulation generally depend upon the subjective response of the patient to the exercise, the limiting factor being the production of pain in the active muscles (*intermittent claudication*). The simplest test consists of having the patient walk at a definite pace until he experiences the symptoms, and determining either the distance covered (*claudication distance*) or the exact time of the initial appearance of the complaint (*claudication time*) It is obvious that motivation has an important influence on these figures, since the end point is affected markedly by the patient's reaction to a painful stimulus Nevertheless, for clinical purposes, information derived in this fashion is adequate, provided the patient's word can be trusted and no ulterior motive exists to cause him to exaggerate his reactions or to falsify his symptoms

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Temperature measurements

JOHN F. PERKINS, JR.

Evolution has provided man with homeostatic mechanisms that permit a diurnal variation of only about 1°F above and below an internal (rectal) temperature of 98.6°F (37°C) Dubois ridicules the practice of "worshipping the little arrow" on the clinical thermometer which allegedly shows "the exact level of normal," pointing out that the body temperature may be half a degree or more above the arrow without any significance Nevertheless, the simple clinical thermometer proves to be one of the most valuable of all medical instruments, since it is all that is needed to establish the presence of *fever* and determine its severity. This is the first and most important reason why the physician measures temperature

Probably ideally suited for its purpose, the clinical thermometer provides a maximum reading by virtue of a constriction which prevents return of the column of mercury into the bulb Its cost is low, permitting use by only one hospital patient, thereby minimizing contagion It is easily sterilized, and its accuracy, especially if certified by a bureau of standards, is entirely adequate.

At the present time, management of *therapeutic hypothermia* represents a second major field in which temperature measurements are required In the third field, the study of *relative blood flow* in skin or muscle in patients suspected of having disorders of the peripheral circulation, estimation is readily performed by means of temperature measurements. For these latter two applications, electrical methods of measurement are preferable, even though thermometers with flattened bulbs for application to the surface of the skin [1] have been used with a fair degree of success.

There are two commonly used electrical methods for measuring temperature in biology and medicine The first utilizes the thermoelectric principle, discovered by Seebeck (1826), which states that current flows continuously in a closed circuit of two dissimilar metals, when the junctions of the metals are maintained at different temperatures. Such a closed circuit constitutes a thermocouple. The second method utilizes the fact that certain types of wire, or special rare earth compounds, show a change in resistance with temperature.

THERMOELECTRIC METHODS FOR TEMPERATURE MEASUREMENT

The "measuring" and "reference" junctions of a pair of thermocouples can be made by soldering or welding together wires of copper and constantan (a copper-nickel alloy) (Fig. 3-59). The copper arm of the measuring junction at 30°C would be 407 μv positive with respect to that of the reference junction at 20°C, a figure determined from tables in the *Handbook of Chemistry and Physics* [2] for the specific range from 20 to 30°C, each degree of difference prod[illegible]

[illegible] couples, which have the disadvantage of tending to rust

USE OF THERMOCOUPLES WITH POTENTIOMETERS

Thermoelectric potentials can be measured, first, with a null-balance potentiometer, in which a

[1] Obtainable from Rascher and Betzold, Chicago. Range 20 to 40°C.
[2] Chemical Rubber Publishing Co , Cleveland.

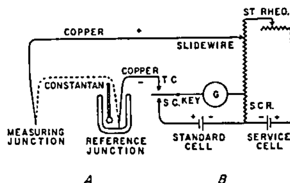


Fig. 3-59. A. A pair of thermocouples made from copper and constantan wire. Difference in temperature between "measuring" and "reference" junctions (in thermos flask with thermometer) produces approximately 40 μv (40×10^{-6} volts) per degree centigrade B Basic circuit of null-balance potentiometer for accurate measurement of small electrical potentials, as described in text.

source of unknown potential (here a thermocouple pair) is compared with a known potential of same polarity. The latter is varied by means of a moving contact on a calibrated resistance, called a slidewire, through which current flows from a battery (service cell). When a sensitive galvanometer (G) shows no deflection with the switch at position T C., the point of balance has been reached and the known and unknown potentials are equal The instrument is standardized at frequent intervals (switch momentarily at S C), the current in the service-cell circuit being adjusted by the standardizing rheostat (St Rheo) until the voltage drop across the service-cell resistance (S C R) equals that of the standard cell Developing a precisely known voltage, the latter is too delicate for sustained service. The fact that a potentiometer draws no current through the external circuit at point of balance is advantageous when measuring temperature with thermocouples, the resistances of which may be permitted to differ by considerable amounts, as when it is desired to use wires of different diameters or lengths, without affecting the measurement

Precision potentiometers[3] are used when it is necessary to measure temperatures to within 0 1 to 0 01°C using thermocouples, as in climatic research laboratories engaged in measuring the insulating properties of clothing Such measurements require considerable time, both for balancing the instrument and in order to convert the readings of potential into temperature by means of tables.

Commercially available, portable (12 lb), and rugged potentiometers of the manually balanced type[4] may be conveniently used for measurement of skin or rectal temperatures, their accuracy to within 0.2°C being entirely adequate for that purpose. Readings are given directly in degrees centigrade or degrees Fahrenheit without reference to tables; automatic reference junction compensation eliminates the need for a reference bath, and as many as 12 thermocouples may be used in sequence by the addition of a selector switch

When self-balancing potentiometers are used for recording several temperatures with thermocouples alone, if rapid changes in the temperature surrounding the instrument are not made, the types using automatic reference junction compensation are satisfactory and are widely used in industry For use in biologic research and in medicine, the so-called uncompensated types are in the author's experience preferable since the temperature of the air and at several points on the skin may be individually measured by means of thermocouples, followed in automatic sequence by rectal temperature measured by resistance thermometer. A reference-junction bath (Fig. 3-60) is required for the thermocouples when an uncompensated instrument is used.

Excellent self-balancing industrial-type potentiometers[5] that automatically record temperatures by means of thermocouples on a circular or strip chart are most useful when one desires to measure skin, rectal, and room temperatures during clinical evaluation of peripheral circulation in man, and during research on man or experimental animals. Their additional initial cost is often offset by the reduced need for technical personnel. Though too heavy (70 to 100 lb) to be carried, these instruments are easily moved on wheeled tables

Where cost is a factor, a simple, though relatively accurate, instrument can be assembled using a galvanometer connected through a selector switch to two or more pairs of thermocouples, the cost depending on the quality of the galvanometer and switches. For a range from 0 to 50°C, a relatively insensitive galvanometer, 2 to 5 μv/mm deflection, 16 ohms coil resistance, will suffice. If one desires to measure rectal temperature over a narrow range, say 32 to 42°C, an instrument with a sensitivity of 0.5 to 2 μv/mm, 16-ohm coil, would be required.

Thermocouples are made from copper and constantan wires, running together in braided spun

[3] Type K3 potentiometer No 7553, Leeds and Northrup Co., Philadelphia.

[4] D C Potentiometer No. 8663, direct-reading indicator, for iron-constantan thermocouples Range 3.9 to 51 7°C; accuracy, 0 3 per cent of range Leeds and Northrup Co., Philadelphia.

[5] Speedomax type H, model R (round) and S (strip) chart recorders, for measuring 1 to 24 temperatures. Leeds and Northrup Co, Philadelphia. Honeywell ElectroniK Recorders—circular or strip chart models, 1 to 24 temperatures, Minneapolis-Honeywell, Philadelphia

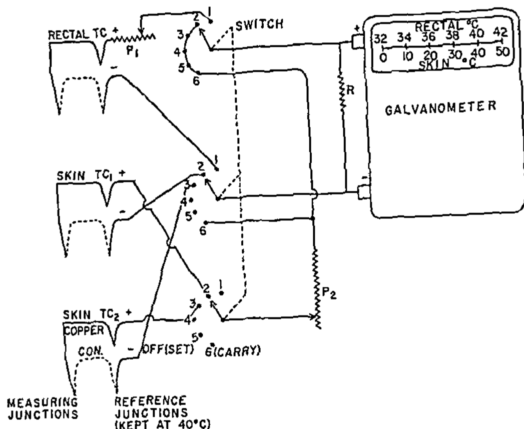


Fig. 3-60. Galvanometer and thermocouples used to measure skin temperature. Placing the reference junctions in a water bath regulated at 40°C provides two ranges of temperature.

glass insulation,[6] wire sizes ranging from No 24 (0 02 in. diameter), relatively heavy and stiff, down to No. 30 (0 01 in.), fairly thin and flexible. *A measuring junction is prepared at one end* by twisting and soft-soldering together the bared tips of the two dissimilar wires.[7] At the other end, not only the constantan but also the copper wires are soldered to separate enamel- and nylon-insulated copper wires, thus *forming the reference junctions* These are insulated with small lengths of electrical spaghetti or plastic tubing, and attached to the bulb of a laboratory thermometer calibrated from −5 to +50°C in 0 2° divisions The thermometer and reference junctions, enclosed in a small rubber or plastic bag so as to keep them dry, are immersed in water in a thermos flask, which can be further thermally insulated by surrounding it with cotton. By keeping the copper-copper junctions in the reference bath, parasitic potentials are minimized, and a neat connection is made to the paired thermocouple cable. The copper wires are led to a selector switch, the output of which is connected to the galvanometer (Fig. 3-60) A temperature scale extending the length of the linear deflection of the galvanometer may be attached to the latter, using a range of 0 to 50°C (or 10 to 40°C, if desired) for clinical studies or research on peripheral circulation With the galvanometer shunted by the critical *damping resistance* (*switch to* OFF), the indicating light beam is moved by the mechanical adjustment until it points on the scale to the temperature of the reference bath, close to that *of room* temperature.

[6] The following components are used: galvanometer—No. 3400, H, Rubicon Co, Philadelphia, or type E galvanometer, No 2430 A, Leeds and Northrup Co, Philadelphia. Less sensitive galvanometers will suffice (see text). Also, the Minneapolis Honeywell Electronik "Null-Balance Indicator" may be used in place of a galvanometer,

75 ohms, P_1, P_2, 500-ohm General Radio potentiometers, type 975, or similar. The thermocouple for measuring rectal temperatures should be embedded in a copper probe

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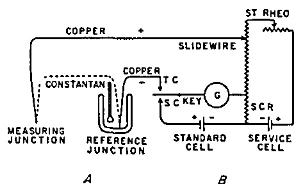


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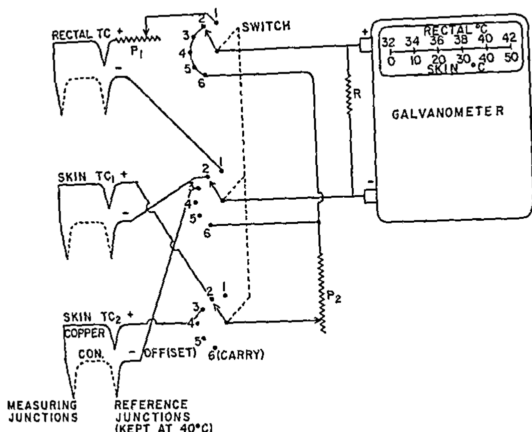


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[7] A procedure facilitated by use of liquid plastic resin soldering flux, formula 415, Kester Solder Co., Chicago.

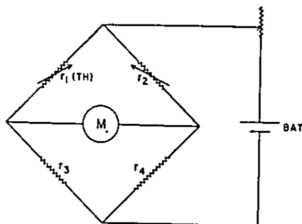


Fig. 3-61. Basic circuit of Wheatstone bridge for measuring unknown resistance r_1, here a resistance thermometer *TH*, the resistance of which has been determined for various temperatures.

During initial calibration, the measuring junctions are fastened to the bulb of a good laboratory thermometer and immersed in a motor-stirred bath of water at a temperature within that of the range of the scale, and as far removed as possible from that of the reference bath The galvanometer may now be made to give the correct temperature reading by adjustment of P_2 (Fig 3-60). This relatively high resistance is placed in series with the thermocouples so that moderate changes in the resistance of the latter, due to variations in their length or temperature, will have little effect on the readings The circuit is arranged so that an external resistance close to that for optimum "critical" damping of the galvanometer is always present For carrying the instrument, which is relatively delicate, a short-circuiting position is provided on the switch.

By immersing the reference junctions in a thermoregulated bath at exactly 40°C (Fig 3-60), an additional range of temperature may be added for measuring rectal temperature over a range of 32 to 42°C, 40°C being located at the same position on both scales When the selector switch is moved to position 1 (for measuring rectal temperature), a greater deflection is produced for a given temperature change, correct adjustment being obtained with potentiometer-rheostat P_1

When extremely small thermocouples are desired, for insertion into fine hypodermic needles during measurement of intramuscular temperatures, or for implanting in the brain of animals, insulated copper and constantan wires are available in sizes down to No. 40,[8] only 0.003 in in diameter. In order to avoid an excessively high electrical resistance in the thermocouple circuit, relatively short (1 to 2 ft) lengths of the very fine wires are connected to thermocouple extension leads of heavier wire which lead to the reference bath as before, copper being always connected to copper, and constantan to constantan.

RESISTANCE THERMOMETERS

Wires made from all but a few alloys show an increase in electrical resistance on warming This property has led to the development of resistance thermometers. The basic circuit involves the use of a *Wheatstone bridge* (Fig. 3-61) in which voltage is applied across one pair of opposite corners, and potential is measured between the remaining pair.

When, by varying one of the resistance arms, say r_2, the bridge is balanced (i e, no potential is picked up by the meter) and if the resistances of r_2, r_3, and r_4 are known, then r_1 (unknown) = $r_2 \cdot r_3 / r_4$. With a resistance thermometer *TH*, such as a coil of fine platinum wire, located at position r_1, its resistance, which is a function of temperature, can be measured. Since the change of resistance of such a thermometer is small, highly precise and rather costly Wheatstone bridges, either of the manually balanced or self-balancing type, are necessary. During the past several years, however, it has been found that oxides of certain rare earth elements such as zirconium show a marked change in resistance, actually a decrease, with increase in temperature (negative coefficient of resistivity). Relatively inexpensive resistance thermometers called thermistors have been developed using these materials, they can be used to measure temperature with a Wheatstone bridge, utilizing a relatively inexpensive microammeter. In this application, the bridge is in balance at just one temperature, say 30°C, higher or lower temperatures producing imbalance with almost linear deflections of the meter over a range of 20 to 40°C. A satisfactory circuit for this purpose has been previously described. The author has modified this circuit slightly for use with rectal probes for measurement of body temperature during hypothermia for cardiac surgery, the circuit being arranged so that thermistors of the same type, though with slightly different resistances, can be plugged into specified sockets, individual settings being made for each thermistor by means of resistances P_2 and P_3, labeled "SET T_1 and T_2" (Fig 3-62)[9] These are adjusted so that the bridge is balanced i e, the meter gives no deflec-

[8] W. B. Driver Co, Newark, N.J.

[9] The following components are used. R_1-R_6—IRC type WW10 J, 0 15-watt resistor, P_1-P_4 Ohmite-type CLU potentiometers, M· 50-0-50 microammeter, about 2,000 ohms, 4½-in rectangular Triplett No 420, or Simpson No 29, or Phaostron Deluxe, T_1, T_2 No. 14B thermistor, 2,500 ohms at 25°C, Victory Engineering Co, Union, N.J, SW_1, three-section ceramic wafer, silver-plated, four or more positions. Excellent switches

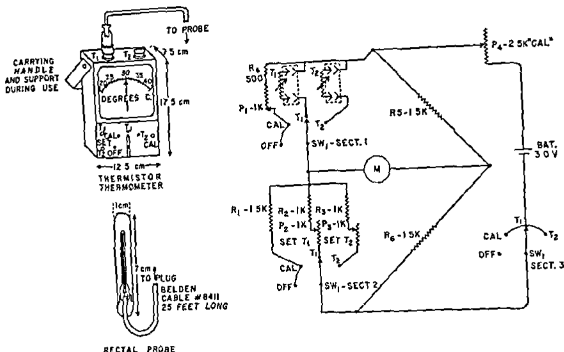


Fig. 3-62. Thermistor resistance thermometer for measuring rectal temperatures during therapeutic hypothermia or other procedures. The circuit consists of a Wheatstone bridge

tion with the thermistors in a motor-stirred bath at exactly 30°C. The bath is then warmed to 40°C and the 2.5 K "cal" rheostat, P_4 is adjusted until the pointer reads 40°C. If good electrical components have been used, the meter will also read 20°C with the probe at that temperature. After these procedures have been completed, the selector switch is turned to "cal" and rheostat P_1 is adjusted until the pointer is deflected to 40°C on the scale. P_1 is locked permanently in this position. Before each use of the instrument, the selector is turned to "cal." If the pointer is not deflected exactly to 40°C, then the "cal" rheostat (P_4) is adjusted until it does. Need for repeated adjustment suggests a failing battery, which should be replaced.

Complete thermistor thermometers are now available commercially,[10] already calibrated, with a variety of probes for measuring air, skin, rectal, esophageal, muscle, bone, or venous (by hypodermic needle probe) and intracardiac (by radio-opaque catheter) temperatures (Fig. 3-63). Thermistor bridge circuits[11] without meters are also available for use with self-balancing potentiometers.

Ten years of use of thermistor thermometers for determining both rectal and air temperatures has convinced the author of their excellence for these applications, and the recent development of small surface and internal probes should make them ideal for clinical evaluation of peripheral circulation.

with solid silver contacts made by Oak Mfg. Co., Chicago, may be obtained in small quantities through the courtesy of Grass Instrument Co., Quincy, Mass., bat., two, size D 1.5 V flashlight cells, Ray-O-Vac No. 4LP, connected in series. The rectal probe, of copper, houses the type 14B thermistor. Armstrong's A-1 Adhesive (Armstrong Products Co., Warsaw, Ind.) is used to fill the cavity where the electrical connection between

indicated. Other types of unmounted thermistors can be purchased from Victory Engineering Co., Union, N.J., Fenwal Electronics Co., Boston, Mass., Gulton Industries, Metuchen, N.J., and General Electric Semiconductor Products, Edmore, Mich.

Yellow Springs Instrument Co., Yellow Springs, Ohio.

[10] Obtainable from the Waters Corporation, Rochester, Minn., and the Yellow Springs Instrument Co., Yellow Springs, Ohio.

[11] E. H. Sargent and Co., Chicago, who also manufacture thermistor thermometers and probes.

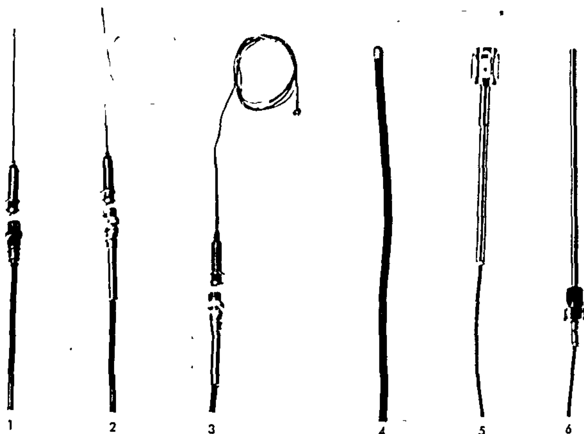


Fig. 3-63. Several types of commercially available thermistor probes. 1. Hypodermic needle probe, in gauges 18, 20, or 22 2. Probe for chronic implantation in tissues 3. Surface, "banjo" type probe for surface temperature (can be taped in place) 4. General purpose, oesophageal-rectal probe. 5. Air temperature, stainless steel probe. 6. Liquid immersion, stainless steel probe, useful in blood-oxygenator machines. Probes 1–3, and another version of 6, have detachable leads and are autoclavable. (*Courtesy Yellow Springs Instrument Co., Yellow Springs, Ohio*)

However, for experiments on unanesthetized animals, who sometimes chew off electrical temperature-measuring devices, thermocouples, because of their ruggedness and low cost, are probably unsurpassed at present. It should also be pointed out that all resistance thermometers, including thermistors, are heated, even if only a fraction of a degree, by the electric current passing through them. This error, which can be minimized by using very small currents and sensitive measuring devices, does not exist with well-constructed thermocouples.

Developments in direct-coupled, multiple-channel, direct-writing recorders[12] or photokymographs[13] permit use of either thermocouples or thermistor thermometers for recording temperature simultaneously with the electrocardiogram and with blood pressure, oxygen saturation, oxygen and carbon dioxide tensions, and other variables

[12] Grass Instrument Co, Quincy, Mass, Offner Electronics, Chicago.

[13] The Waters Corporation, Rochester, Minn; also "Visicorder," Minneapolis-Honeywell Co, Philadelphia

RADIATION THERMOPILES AND BOLOMETERS

Even small thermocouples, together with the means of attaching them to the skin (adhesive tape or collodion), act as thermal insulation and hence cause a rise in the very temperature being measured. For this reason, a physical law relating heat radiation to the fourth power of the absolute temperature of a body has been applied in the use of another instrument for the measurement of temperature. The instrument, called a *radiation thermopile*, consists of a conical heat receiver, covered by a window which is directed toward, but does not touch, the object of unknown temperature. The small amount of radiant heat reaching the base of the cone is picked up by a thermopile, consisting of many measuring and reference junctions connected together so as to give correspondingly greater voltage than a single thermocouple pair In recent years, sensitive thermistor bolometers (radiation-sensing devices) have been substituted for the delicate thermopiles

Precise measurements of skin temperatures have been carried out during studies on temperature

regulation, cutaneous sensation, and climatic research using radiation-sensing temperature-measuring devices. Since no wires need be connected to the skin, advantages are gained by their use during certain studies, such as those made on sleeping subjects. For some measurements, moreover, no other device is adequate, as in determining the temperature of the sky from the ground.

Since radiation-sensing temperature-measuring devices are much more difficult to construct and calibrate than thermocouples, an instrument maker or manufacturer[14] is usually required

TEMPERATURE MEASUREMENTS IN MEDICINE AND BIOLOGY

Because measurement of blood flow by occlusion-cuff or photoelectric (photometer-type) plethysmograph is not only technically difficult but often inaccurate, skin temperature has come into wide use as a measure of relative blood flow.

The two have been related numerically by Burton's "thermal circulation index," which applies to steady-state conditions after skin temperature T_S has leveled off, with "core" (rectal) temperature T_R and air temperature T_A also constant.

According to the laws of diffusion of heat, the amount of heat H reaching a given area of skin per unit time is

$$H = C_T(T_R - T_S)$$

where C_T = thermal conductivity; i e , the ease with which heat flows in the tissues
$T_R - T_S$ = temperature gradient along which heat flows

With skin and other temperatures constant, the same amount of heat leaves the skin to reach the air, or

$$H = C_A(T_S - T_A)$$

where C_A = thermal conductivity of air

Thus

$$H = C_T(T_C - T_S) = C_A(T_S - T_A)$$

or

$$\frac{C_T}{C_A} = \frac{T_S - T_A}{T_C - T_S} = \text{T.C I.} \qquad \text{Burton's "thermal circulation index"}$$

Expressed in words: the ratio of the thermal conductivity of the tissues to that of air is equal to the ratio of the external temperature gradient to the internal. At a given humidity and air velocity, C_A is constant, hence changes in the calculated ratio represent changes in C_T. The value of the latter, though influenced by the nature of the tissue (fat vs. muscle, etc.) and the location on the body, is due chiefly to the blood flow at a given location.

The following table illustrates the application of the T.C I. to peripheral circulatory problems. Data were obtained on lightly clad subjects who had been in a room at 20°C until skin temperatures had leveled off. Rectal temperature was 37°C

Location on body	T_S, °C	$(T_S - T_A)$, °C/$(T_R - T_S)$, °C = T C I.		
Forehead	33	13	4	3 3
Big toe	22	2	15	0 13
Big toe during ether anesthesia	30	10	7	1.4

The T.C.I. of the forehead is high, chiefly because there are few vasoconstrictor nerves in this region. The low, though not abnormally so, value for the toe is due to reflex vasoconstriction, one of the heat-conserving mechanisms of the body When this was abolished by ether anesthesia, the T.C I. rose more than tenfold. Plethysmographic measurement of actual blood flow in experiments such as these have indicated that the flow increases by about the same relative amount as the T.C I. For this reason, this index, as determined by temperature measurements, is useful in studies of peripheral circulation, particularly when a change in blood flow can be produced, as in the example cited

A prerequisite to the treatment of peripheral vascular disease is a correct diagnosis of its exact nature. The following examples, modified from White et al , 1952, will serve to illustrate this point. Skin temperature of the toe of patient A was 26°C in a room at 26°C. Assuming rectal temperature to be 37°C, T C I. would be zero (Evaporation, due to insensible perspiration, can actually lower skin temperature below that of the room) After spinal anesthesia, the temperature of the toe rose to 34°C and the T C I. increased to 2.7, representing excellent blood flow. In patient B, with the room at the same temperature, the skin temperature of the toe rose from 26°C (T C I again = 0) before, to 30°C after spinal anesthesia, with the T.C I. increasing only to 0 57, representing relatively

[14] Baird Associates, Cambridge, Mass.

poor blood flow even after abolishment of vasoconstriction. These data helped to confirm a diagnosis of vasospasm due to Raynaud's disease in A, and of Buerger's disease in B. They also indicate that while both patients could anticipate benefit from lumbar sympathectomy, A would probably receive considerably greater relief.

For evaluation of peripheral circulation by studies of this type, reflex vasoconstriction may be abolished not only by ether or spinal anesthesia and by local nerve block, but also by a simpler method which involves warming the body, in a heated cabinet, with the extremities in cool surroundings or by immersing first the upper and then the lower limbs in hot water while measuring the temperature of the exposed digits. Care must be taken to avoid burning areas that have a poor circulation.

Measurement of skin temperature, with or without abolishing vasoconstriction, is also a useful diagnostic aid in the following additional peripheral circulatory conditions, an abnormally high surface temperature being represented by a plus (+) sign, a temperature below normal by a minus sign congenital or acquired arteriovenous fistulas, + above the lesion, – below, trench foot, early hyperemic phase, +, late posthyperemic phase, –, cervical rib (or scalenus anticus syndrome), – in hand or affected side; acrocyanosis, –; erythromelalgia, +; vascular (arterial) spasm and arterial embolism, – below lesion. In the latter condition the opposite side, even with the artery patent, may be cooler because of reflex vasoconstriction caused by the irritation of the embolus

Even with rapid developments in bypass pumps for open-heart surgery, *hypothermia* has achieved a permanent place in surgery of the heart and great vessels, and in surgery of the brain and liver. Because of the increasing danger of ventricular fibrillation as body temperatures fall below 27 to 30°C, reliable measuring equipment is of great importance. In this connection, the copper thermistor probe (Fig. 3-62), though it may seem relatively large, has been used repeatedly in infants without ill effects and has given far more consistent readings than smaller plastic probes. The probable reason is that the latter may become embedded in feces, which insulate the probe from the wall of the rectum.

Routine measurement of body temperature by probe thermistor or thermocouple during any form of prolonged surgery, particularly in infants, may well prove helpful in preventing the hyperthermia and dehydration due to sweating that sometimes occur.

Research into temperature-regulation mechanisms of homeotherms could not have progressed without temperature measurements, particularly electrical ones. The role of the hypothalamus as a reflex center and its sensitivity to changes in the temperature of the blood perfusing it have been demonstrated by Barbour, by Ranson, and recently by Forster in unanesthetized cats by means of thermistor thermometers implanted during a previous operation. Implantation of thermistors and thermocouples at multiple locations in the brain should contribute to the knowledge of cerebral function.

Measurement by tiny thermocouples of the temperature of the air exhaled by the desert rat has contributed to a study of water balance in these animals. With the new, fast-response, high-impedance, chopper amplifiers now available and with thermistors only a fraction of a millimeter in diameter, or thermocouples made from wire a few thousandths of an inch in diameter, the 95 per cent response time of such temperature-measuring devices can be as low as approximately 1/10 sec, permitting studies of the comparative physiology of temperature to be carried out on a variety of small as well as large creatures.

PART 4

Additional methods of examination

1

Electrocardiography

Classic Electrocardiography

EDWARD MASSIE AND EDGAR J. MILLS

Unipolar Leads

FRANKLIN JOHNSTON AND PARK W. WILLIS, III

Electrocardiography in Normal Infants and Children

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CLASSIC ELECTROCARDIOGRAPHY

HISTORY

The history of electrocardiography dates from the end of the eighteenth century. Luigi Galvani (1791) accidentally observed that the muscles of a frog exhibited vigorous contractions whenever sparks were drawn from an electrical machine and the nerves of the preparation were touched with a knife at the same time. He suspected that this phenomenon was related to the electrical discharge and successfully repeated his experiment by connecting a dissected frog to a lightning conductor during a thunderstorm.

Further experiments in animal electricity were carried out by Matteucci (1842) and Koelliker and Mueller (1858), who placed a *neuromuscular frog preparation* in contact with an exposed frog heart and observed contractions of the gastrocnemius muscle with each cardiac beat. Their experiment demonstrated that the heart gives rise to electrical currents and that the electrical events precede mechanical systole. The next advance was made when Sanderson and Page (1878) recorded the cardiac currents in laboratory animals by means of the *capillary electrometer*. Waller (1887) showed that the currents produced by the heart muscle could be recorded in intact animals by the use of surface electrodes, and then proceeded to apply this method to man. The capillary electrometer was sensitive but capricious and difficult to operate. Its use was, therefore, abandoned with the advent of the *string galvanometer* at the beginning of the present century. This instrument was invented by Schweigger but perfected by Willem Einthoven, who introduced it into the field of experimental medical research (1903) and thus inaugurated the era of electrocardiography. As the clinical potentialities of the string galvanometer came to be appreciated, its use became more widespread. Other types of apparatus have been invented, and technical improvements are constantly being effected.

During the first quarter of the twentieth century, electrocardiography made considerable strides thanks to the research work of Lewis in London and Wenckebach in Vienna, both of whom made an intensive study of the arrhythmias and various types of heart block. Coronary diseases were studied by American workers between 1920 and 1930.

In 1933 Wilson and his associates described the "unipolar" technique which was used initially in experimental work but has now found extensive clinical application.

In recent years, *spatial vectorcardiography* has come into prominence as a diagnostic method of potentially greater accuracy than conventional electrocardiography, even though technical difficulties make it unlikely that the electrocardiogram will be superseded by this method.

ELECTROCARDIOGRAPHS

The *electrocardiograph* is an instrument that makes it possible to record the potential varia-

tions associated with cardiac action as they present themselves either on the body surface or, in certain instances, in the body itself. The tracing thus obtained is called the *electrocardiogram*.

It must be emphasized that the electrical forces produced by the heart are exceedingly small and undergo rapid changes from instant to instant. For this reason, it is essential that the moving parts of any instrument used to register them have a high degree of sensitivity and a low inertia.

The essential constituent of an electrocardiograph is the *galvanometer*. Three main types of electrocardiographs are in use today.

The String Galvanometer. This instrument was introduced by Einthoven in 1903. It consists of a fine quartz string coated with silver, platinum, or gold, suspended vertically between the poles of a powerful magnet (electromagnet). Each end of the string is connected to a lead wire, which in turn is attached to an electrode placed at a selected site on the patient's body surface.

The cardiac currents flowing through the string (which acts as a linear conductor and is situated in a magnetic field) cause it to be deflected in a direction perpendicular to the magnetic lines of force, in accordance with *Fleming's Left-hand Rule.*[1]

As the mass of the quartz fiber is very small, the unamplified cardiac currents can move it with sufficient speed, the degree of deflection being directly proportional to the voltage. A faithful record of the rapid potential variations can therefore be obtained, especially as little or no "overswing" of the delicate string will occur in view of its low inertia. The excursions of the string are recorded photographically. This is done by means of a suitably placed light source which projects the shadow of the moving fiber onto a film running at a uniform speed. High magnification of the string shadow (up to 800 to 1,000 times) is made possible by a system of lenses (Fig. 4-1).

Such a tracing would not be of much value without the superimposition of a time scale. This is provided by a five-spoked wheel which operates independently of the camera motor and revolves at such a speed as to interrupt the light beam every 0.04 sec. As a result, the shadows of the spokes appear on the film as vertical lines at intervals of 0.04 sec. Because one of the spokes is thicker than the others, every fifth line on the tracing is heavier, and the interval between any two of these therefore corresponds to 0.2 sec.

It is important to measure the height of the various deflections in the completed record. A

[1] *Fleming's Left-hand Rule* (as applied in this instance) states that if the thumb, index finger, and middle finger are held at right angles to each other, and the index finger represents the direction of the magnetic field (from the north to the south pole), and the middle finger the direction of current flow in the string, the thumb will point in the direction in which the string will move.

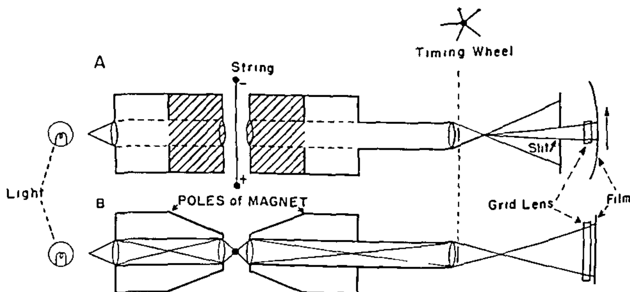


Fig. 4-1. Diagram illustrating the principle of the string galvanometer. A. Side view. B. Transverse section to show the arrangement of the lenses. The position of the timing wheel in the path of the light beam is indicated by the interrupted line. The film moves past the grid lens in the direction of the solid arrow. (*From Barker. The Unipolar Electrocardiogram.*)

"grid lens," mounted in front of the camera and in the path of the light beam, is used for this purpose. The lens is scored with opaque horizontal lines which are 1 mm apart. Every fifth line is thicker than the rest. The shadows of these lines also appear on the film.

The disadvantage of this type of galvanometer lies in the fact that it has a low internal resistance in comparison to the resistance of the skin. As the flow of current through a conductor is inversely proportional to the resistance of the circuit, distortion of the tracing would ensue. Furthermore, skin resistance may vary considerably from one site on the body to another, even after proper preparation of the patient. This may result in the appearance of skin currents which flow from an electrode overlying an area of high resistance to another electrode in contact with an area of lower resistance, and may cause such a marked displacement of the string that the latter may be damaged or even break. These difficulties can be overcome by the inclusion of a *preamplifier* in the circuit.

The earlier string electrocardiographs were unwieldy and could not be moved to the patient's bedside. They have now been superseded by lighter, more compact, portable models which operate on alternating current.

The Mirror Galvanometer (Oscillograph) with Vacuum Tube Amplification. This type of apparatus is sturdier than the string galvanometer and is also more complex in its construction. The *oscillograph* consists of a coil (or loop) of wire suitably suspended in the field of a permanent magnet. The coil carries a mirror which reflects a beam of light focused upon it onto photographic paper. Various modifications of this basic principle are employed in different models. These machines are generally portable and operate on either a-c (alternating current) or batteries. The moving parts of the galvanometer constitute a greater mass than the delicate quartz string so that the sensitivity of the instrument is inevitably reduced. The cardiac currents are too small to produce sufficient movement of the coil and mirror and, therefore, have to be augmented before they enter the oscillograph. This is done by the inclusion of an *electronic vacuum-tube amplifier* in the circuit. The amplified current flowing through the wire loop produces electromagnetic lines of force which interact with those of the magnetic field in the same manner as was outlined for the string galvanometer. As a result, the loop undergoes a twisting movement. The mirror likewise rotates, and the corresponding excursions of the light beam are recorded photographically. Its deflections are proportional to the current flowing through the loop.

There are several different models representative of this type of electrocardiograph, an example of which is the *Sanborn Twin-Beam Cardiette*. This twin-channel instrument facilitates the simultaneous registration of two electrocardiographic leads but can also be used for the recording of heart sounds in conjunction with an extremity lead which then is used for timing the cardiac sounds and murmurs. Two high-speed galvanometers are incorporated in this machine; their sustained frequency response, therefore, makes them suitable for research work on small animals.

The Direct-writing Electrocardiograph. This is a type of oscillograph which requires still higher amplification for its operation. The reason for this lies in the fact that, in these instruments, a spool situated in a magnetic field forms the conducting unit which by its movements activates an attached rigid writing arm (stylus). The tip of the stylus in its turn inscribes the actual tracing. The necessary degree of amplification is attained by the use of a preamplifier and an amplifier the output of which is transmitted to the galvanometer. These machines are usually portable and operated by alternating current. Two types of direct-writing electrocardiograph are in use, namely, *ink writers* and *thermic writers*.

The *ink writer* is provided with a rapid-feeding point and has the advantage that no special processing of the recording paper is necessary, which makes for greater economy. The time coordinates have to be curvilinear as the stylus writes in an arc. Its disadvantages are the messiness associated with the servicing of such an instrument and the periodic clogging of the mechanism.

The *thermic writer* is the type which is most used for clinical purposes. The tip of the stylus is heated and produces the tracing. The recording paper has to be specially processed and is therefore more expensive. It has a thin surface layer of white wax or plastic material which melts when brought into contact with the glowing stylus, with the result that the underlying black layer is revealed. The black tracing obtained stands out well against the white background. However, the paper has the disadvantage of being easily scratched and turning diffusely black if accidentally exposed to high temperatures or certain liquids, such as the glue used for mounting records. Various types of writing arms are employed which have thermic writers. A stylus with a heated jewel point does produce a thin tracing, but as it is pivoted and therefore moves in an arc over the paper, the electrocardiographic complexes are also curved. Paper with equally curved time coordinates is therefore necessary. This drawback has been overcome in two different ways.

In some models (Sanborn, General Electric), the paper is sharply angulated and is made to pass over a metal "knife edge." The stylus tip carries

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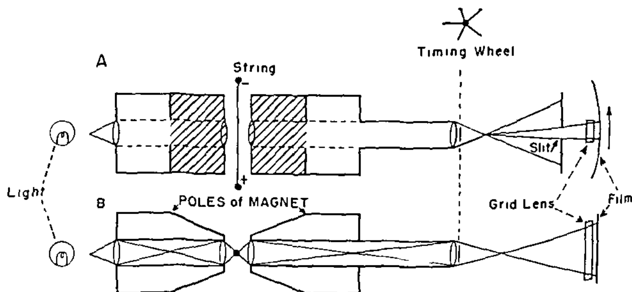


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lem of maintaining contact between the electrode in its different positions and the moving chest wall is more difficult than in the limbs, and various devices are therefore used:

1 *Electrodes with insulated handles* can be held in place either by an assistant or even by the patient himself This method may introduce artifacts into the tracing if the handle is contaminated with conducting jelly, if the relative humidity is high, or if the person holding the electrode has perspiration on his hands

2 *Suction-cup electrodes* are popular because they stay in place without outside assistance. They are also useful for application to limbs which are the site of an intravenous infusion. However, they are likely to slip off at the critical moment and are also more difficult to keep clean

3 The problem is solved most easily by the use of a *plastic strap* with weighted ends which is placed across the patient's chest. If this is properly done, the electrode can be maintained in any desired position.

It should be noted that, with a certain amount of practice it is possible to dispense with external fixation [illegible] leads by [illegible] the lead wire is slack. [illegible] electrode in place, even on the lateral chest wall If necessary, the patient can be instructed to hold his breath.

Electrodes of smaller dimensions must be used for infants and young children

Needle electrodes, inserted subcutaneously, can be used when tracings cannot be obtained by conventional methods, as, for instance, from patients subjected to hypothermia by immersion in ice water.

ELECTROCARDIOGRAPHIC TECHNIQUE

At present, the recording of an electrocardiogram does not call for great technical skill, therefore, every medical practitioner should be capable of taking a technically satisfactory tracing on a reasonably cooperative patient Experience has shown, however, that this is not always the case, because elementary precautions are commonly neglected, with the resultant introduction of artifacts

Apart from the electrocardiographic apparatus itself, the following *accessories* are required for the completion of the circuit

1 Power cable. This connects the machine with the external power supply.

2. Patient cable This is usually made up of five separate lead wires, one for each of the extremities and one for the chest lead. It connects the electrodes with the galvanometer.

3. Electrodes. These have already been described.

4. Electrode paste. This consists of a water-soluble jelly containing sodium chloride and a mildly irritant abrasive, such as pumice powder, and acts as a conductor.

The initial step in the use of electrically operated instruments consists of connecting the apparatus to the power supply since the amplifier type of electrocardiograph requires a *warming-up period*. Certain thermic writers are grounded automatically through the power line, provided the polarity of the power cable is correct. In the *Sanborn Viso-Cardiette*, for instance, this is determined by means of an indicator consisting of a small neon bulb in a grounding disk. If the bulb glows when a metal band on the disk is touched lightly with the finger, the polarity is wrong. Proper grounding will then be established by reversing the power plug. This seemingly minor detail is mentioned specifically because it is frequently not observed and unfortunately constitutes a common source of a-c interference in the tracing.

While the machine is warming up, the nature and purpose of the test should be explained to the patient and any apprehension on his part allayed. The supine or semirecumbent positions are best as they promote muscular relaxation, and the troublesome artifact due to muscle tremor is thereby largely eliminated. For the same reason the room in which the test is performed should be at a comfortable temperature. A bed with a firm mattress, of sufficient length and breadth to accommodate the tall as well as the obese patient, is essential. Stretchers and examination couches are too narrow as a rule to allow the patient to place his arms comfortably by his side and are therefore not as suitable Orthopneic patients should be propped up with pillows and a notation made to that effect as the electrical position and axis of the heart may vary with the posture. If necessary, a chair may be used, provided it is comfortable, has wide arm rests, and is not made of metal As alternating current can enter the patient from the floor, a wooden footstool or several towels should be placed under his feet. For similar reasons, care should be taken that no part of the body of a recumbent patient is allowed to touch any metal part of the bed.

Proper preparation of the skin with electrode jelly is an important prerequisite to a sat-

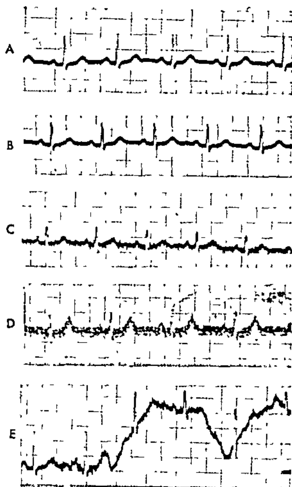


Fig. 4-2. A Stylus correctly centered B. Reduction in amplitude of the QRS complexes which occurs when the stylus is allowed to drift towards the edge of the paper. This is due to a built-in protective mechanism designed to prevent breakage of the stylus in direct-writing electrocardiographs C. Somatic tremor. D. Alternating-current interference. E. Wandering of the base line in a standard lead caused by movement of a limb by a restless patient

a heated band and touches the paper only where it sweeps over this edge Paper with the more convenient rectangular coordinates can therefore be used. This method introduces a small tangential error, i.e., the complexes are falsely magnified, but this is so slight that it may for practical purposes be disregarded

In the Cambridge direct writer the stylus is mounted above the paper, which is curved in an arc identical to that described by the tip of the stylus. This modification eliminates the tangential error and at the same time permits the use of paper with rectilinear coordinates

A protective mechanism limits the excursions of the stylus near the edges of the paper, with resultant blunting and reduction in the amplitude of the complexes; however, damage to the writing arm is thereby prevented. Proper centering of the stylus is therefore imperative (Fig 4-2A).

The *cathode ray oscillograph* may also be employed to record electrocardiograms, but high amplification of the cardiac voltage is necessary for this purpose. It consists of a *vacuum tube* in which a cathode is situated at one end. The glowing cathode emits a stream of electrons which is suitably focused and accelerated by two anodes The beam then passes between two pairs of deflection plates and finally impinges on a fluorescent screen at the opposite end of the tube. The amplifier of a direct-writing electrocardiograph can be used, its output being transmitted directly to the horizontal pair of plates which is responsible for the vertical deflections of the beam by virtue of the potential difference thus created. The size of the deflections is proportional to the difference in potential existing between the plate surfaces A second pair of plates is mounted vertically and causes the complexes of the electrocardiogram to move horizontally from left to right.

In this manner the electrocardiogram can be viewed directly on a fluorescent screen over long periods of time, and the waste of recording paper is avoided This method is particularly suitable for patients undergoing cardiac surgery, as both surgeon and anesthetist can immediately observe any changes in cardiac rhythm during the procedure. The chief advantage of the oscilloscope over the other machines lies in the fact that it has a uniform frequency response and a beam which is devoid of inertia. If necessary, the tracing can be photographed on a moving film.

ELECTRODES

In the early days of electrocardiography, *immersion electrodes* were in general use for ambulant patients. They consisted of an outer vessel of glazed porcelain containing a saturated solution of zinc sulfate and a zinc plate to which the lead wire was attached. The limbs were placed in an inner, porous container filled with normal saline solution Patients confined to their beds had to have electrodes in the shape of broad metal cuffs tied to their extremities, with interposed gauze pads soaked in saline solution acting as a conducting medium The use of this cumbersome equipment has long since been abandoned.

Most electrodes today are made of german silver This alloy is particularly suitable since it has a low electrical resistance and does not possess any polarizing properties. *Limb electrodes* are rectangular, measure 5 by 3 cm on the average, and are slightly curved to ensure proper contact with the skin. They are secured to the extremities by means of adjustable rubber straps. A thumbscrew holds the tip of the respective lead wire in place.

Chest electrodes have a flat contact surface, are circular, and average 3 cm in diameter. The prob-

both are distorted and neither is of any value.

Twelve leads are now recorded in a routine fashion. They are marked on the selector switch on the control panel in the order in which they are usually taken. (1) the three bipolar limb leads (*I, II, and III*); (2) the three augmented unipolar limb leads (aVR, aVL, and aVF); (3) the six unipolar precordial leads (position "V").

The necessary connections for each lead are established automatically by the simple process of turning the selector switch to the desired position The various CF, CR, and CL leads are also represented on the dial although they are now seldom used.

ARTIFACTS

Artifacts are commonly seen in electrocardiographic tracings, and their causes are numerous Some of them, together with preventive measures, have already been discussed. In the majority of instances, the fault lies either in the patient or in the arrangement of the connections rather than in the apparatus itself, and the remedy, therefore, is usually relatively simple

Several distinct types of artifact can be recognized

Muscle Tremor (Somatic Tremor). This manifests itself as irregular oscillations of varying rapidity which are superimposed on the tracing and may be sufficiently pronounced to make a confident interpretation of the record impossible (*Fig. 4-2C*) The most common cause of this type of disturbance is the state of the patient, who may be tense, apprehensive, or uncomfortable *Hence the need* for explanation and reassurance prior to the test A *good technician* is invaluable in this respect. One not infrequently sees records which show somatic tremor in the record of the first lead or two, while the remainder of the tracing is free from this artifact, indicating that the patient has settled down Reflex muscle spasm may be set up in a limb if the electrode strap has been applied too tightly, it is therefore important to check this point.

The fine tremor of thyrotoxicosis and the coarse tremor of Parkinsonism may constitute a problem In such cases it may be necessary to move the limb electrodes from their original sites to the root of the extremity or extremities involved, where such involuntary *movements* will be found to be minimal

Alternating-current Interference. This is an extremely common cause of artifact and is characterized by perfectly regular, fine oscillations occurring at the rate of 60 per second. (Hence the term "60-cycle" interference, *Fig. 4-2D.*) Electrical equipment of any kind may be the source of this type of disturbance. The patient's body acts as an antenna, as it were, picking up any alternating current in the vicinity which then enters the apparatus through the patient cable. X-ray machines, diathermy apparatus, and electric motors of various types are *the most troublesome* sources of interference and should therefore be disconnected before a tracing is taken Electric blankets, heating pads, and hearing aids should always be removed from the immediate vicinity. The electrocardiograph itself must be properly grounded. The self-grounding mechanism incorporated in some of the newer models has already been mentioned.

Alternating-current interference may manifest itself in all the leads of an electrocardiogram or may be confined to certain leads only. If it is generalized, all electrical equipment in the vicinity of the patient, such as table lamps, radios, and electric fans, should not only be switched off but also disconnected from the power supply. It may on occasion be necessary to move the patient to the part of the room where interference is least pronounced. The possibility of introduction of alternating current through the floor should not be forgotten, even though it may be covered with linoleum. *A wooden footstool should be used for* chair patients, while recumbent subjects must be prevented from touching any metallic part of the bed A *tall patient's feet may inadvertently* make intermittent contact with the foot of the bed. Perspiration is an additional aggravating factor in this instance. The problem is solved most readily by instructing him to wear his slippers. The leather covering of [illegible] casions be r[illegible] sheet will ob[illegible] be grounded routinely through the right leg electrode, regardless of the number or types of leads taken

Electrocardiograms may have to be taken under unfavorable conditions, such as in a private home, where there may be defective or unshielded wiring. A long emergency ground wire is useful in such circumstances One end of this wire is attached to the control panel of the machine, while the other end is connected to a radiator or drainpipe If this is not readily available, one of the screws holding the wall plate of an electric outlet in position can be loosened slightly and utilized as a point of attachment. Bedsprings can also be grounded in this way, if necessary.

Alternating-current interference appearing only in two standard limb leads should immediately direct one's attention to the extremity which is

isfactory tracing. The purpose of this step is to reduce the skin resistance and to ensure good electrode contact. The flexor surfaces of the forearms and the sides of the calves are generally selected, but any part of a limb will serve the purpose without prejudice to the final tracing, although hairy regions and areas overlying bone are best avoided. Even amputation stumps may be used unless muscle tremor manifests itself in them In such cases, it is better to place the electrode over the buttock or over the scapular region. A small amount of the electrode paste is applied to each limb and rubbed well into the skin with a tongue depressor or with the edge of the electrode itself until a mild erythema is produced which serves to reduce the resistance Patients with a dry skin exhibit a higher resistance, and this calls for more vigorous preparation. A toothbrush serves well for this purpose The electrodes are then placed over the prepared areas and secured by means of the rubber straps which should be tight enough to insure firm contact between skin and electrode but not sufficiently tight to cause hypertonus. Any excess of paste should be wiped off. The right leg electrode plays no direct part in any of the leads but serves as a means of grounding the patient. The points of electrode placement for the precordial leads should be marked accurately on the chest wall with a skin pencil before the jelly is applied. This is especially desirable if serial records have to be taken in rapid succession, as even slight differences in electrode position may significantly alter the configuration of the complexes and make comparison of serial tracings more difficult. Skin preparation is carried out in the same manner as on the extremities, except that on rare occasions excessive hair on the chest may have to be shaved off first In thin patients, the electrode should always be placed over an intercostal space (not over a rib) in order to maintain contact. The interspace which is closest to the anatomically determined point is the logical choice.

One important problem in the chest leads concerns the *distribution* of the *conduction jelly*. The points of electrode placement are relatively close together, especially in children and individuals with small chests, so that a pool of jelly in one area may easily make contact with a similar quantity at an adjacent site If this happens, the potential variations of one area are conducted to the other, with resultant distortion of the tracing. The net result would be equivalent to an increase in the surface area of the exploring electrode. It is therefore good practice to wipe the jelly off the area in which a lead has been recorded before moving to the next position.

Once the electrodes have been secured, the patient cable is attached to the machine and the tips of the lead wires are connected to the respective electrodes. The cable tips are marked with letters and also have distinctive colors. Nevertheless, accidental *reversal of the lead wires* is not at all uncommon. The tip of each wire should be inserted fully into the binding post of the electrode and secured firmly with the thumbscrew.

If tracings are to be assessed and compared with one another, it is obviously important for a relationship to be established between the amplitude of a given deflection and the voltage it represents. The *standardization of the machine* must, therefore, be checked before each tracing. By long-standing agreement, records are standardized in such a way that a current of 1 millivolt (mv) introduced into the circuit produces a deflection of 10 mm. All types of machines therefore have a special standardization button as well as a sensitivity control knob. The film or paper is set in motion and the standardization button, which introduces 1 mv into the circuit, is depressed repeatedly while the lead selector switch is in the "standard" position. The resulting deflections should be 10 mm in height and have a rectangular outline if the machine is critically damped. If the amplitude of these deflections is not 10 mm, the necessary correction must be made by adjusting the sensitivity control.

In string galvanometers, which have a low internal resistance, the standardization has to be adjusted for each lead, but this is not necessary in the amplifier types of electrocardiograph However, it is the authors' practice to register the standardizing impulse repeatedly while the tracing is being recorded so that it may appear in some of the strips of the mounted record It should be timed in such a way that it is introduced during the normally isoelectric T-P interval. Failure to do this may lead to the superimposition of the calibration deflection on a complex, with the result that

ble cause which is frequently overlooked is tension on one or more of the lead wires which in turn will interfere with proper electrode contact The instrument should therefore always be positioned close enough to the patient to allow the wires to remain slack Dirty electrodes may also be responsible for base-line alterations in certain leads. Continuous wandering of the base line in all leads may be due to a fluctuation in the external voltage supply Many present-day instruments have a built-in voltage-regulating system which should compensate for such changes If this type of artifact is restricted to the precordial leads, it will probably be found to be related to the patient's respiratory movements

Irregular and Bizarre Deflections. This type of artifact is also known as the "jittery" base line. The usual causes are inadequate preparation of the skin, electrodes which have been applied either too tightly or too loosely, or a faulty connection between an electrode and a lead wire (Fig 4-3A) If the disturbance is confined to two limb leads, a broken lead wire should be suspected. A more remote possibility is contamination of the electrode jelly with small metal particles These may gain access either from the tube itself if the screw cap is faulty, or, more commonly, as a result of the operator's failure to keep the tube closed when it is not in use Industrial metal workers are likely to have a coating of metallic dust on their forearms It is therefore advisable to cleanse the skin thoroughly over the prospective electrode sites before taking any tracing from such patients. If the artifact cannot be explained on these grounds, an electrical defect in the instrument is probably responsible.

Artifacts of Direct Writers There are certain artifacts which are peculiar to thermic direct writers and can be traced to a faulty stylus A technically satisfactory record should be black and have a clear-cut base line of even thickness. A grayish tracing with a blurred base line may be due to a number of factors·

1 *Insufficient heat at the stylus tip* This can be corrected by adjustment of the temperature control knob (Fig. 4-3C).

2 *Accumulation of plastic material on the writing point* The stylus can readily be lifted off the paper so that the plastic can be melted off by turning up the temperature control

3 *Insufficient stylus pressure against the paper* This can be adjusted until a satisfactory record is obtained

4 *Damaged stylus ribbon* This occurs in machines operating on the knife-edge principle. The ribbon may become bent after prolonged use, with the result that it makes uneven contact with the paper It can be smoothed out after removal of the writing arm.

Transposition of Lead Wires. This is not an artifact in the strict sense of the word but may be included under this heading for the sake of convenience It is a sign of negligence or undue haste on the part of the operator, and the resultant tracing may be easily misinterpreted. The most common mistake consists of the transposition of the lead wires to the right and left arm. Lead I then mimics a tracing of dextrocardia, and leads II and III will be switched. Inspection of the precordial leads clears up the mystery (Fig. 4-4).

Faulty Damping. Underdamping or *overdamping* of the recording instrument may distort the tracing. This will be dealt with in the next section.

In *summary*, the following general principles should be observed if artifacts are to be eliminated or kept to a minimum: (1) relaxation of the patient; (2) meticulous preparation of the skin, followed by proper application of the electrodes and lead wires; (3) avoidance of drag on the lead wires by suitable positioning of the instrument, (4) use of additional ground wires when necessary; (5) proper care of equipment. Both electrodes and cable tips must be kept clean and shiny. They should be washed with warm water and soap as soon as possible after use, otherwise the jelly will dry up to form a surface film and produce areas of corrosion. These can be removed with sandpaper or a small file if necessary. Steel wool must never be used for this purpose as it will produce polarization of the electrodes, with resulting shifts of the base line. It is also best to avoid using metal polish. The patient cable should be treated with care. Each of the lead wires is made up of numerous thin strands of wire. Some or all of these may break if the cable is bent, twisted, or rolled up too tightly Repair of such damage is costly.

TECHNICAL CHARACTERISTICS OF ELECTROCARDIOGRAPHS

As has already been pointed out, all types of instruments are provided with a standardization (or calibration) button. This device can and should also be used for the purpose of checking certain technical characteristics of the recording mechanism

Damping. The moving parts of a galvanometer would ordinarily tend to continue in motion even after the flow of current has stopped.

common to these leads. In leads I and III, for instance, the left arm is the common member. It should therefore be checked with regard to the following points.

1. Adequacy of skin preparation and electrode contact.

2. Firmness of attachment of cable tip to electrode.

3. Possible contact of left arm with any metal part of the bed or an adjacent wall. Hidden wiring in a wall may have more effect on the extremity nearest to it than on the others, and suitable rotation of the bed may remedy the situation. A newly painted wall frequently is the source of alternating-current interference, even though the patient may not be in actual contact with it.

4. A partially broken cable is a more infrequent cause of trouble.

Alternating-current interference in the precordial leads only should be investigated in the same way as outlined above. The use of a chest electrode with an insulated handle is a common source of artifact for reasons previously discussed. The plastic chest strap is superior in every way and also more convenient. The possibility of a defective chest lead wire must be borne in mind, particularly if interference appears in all the precordial leads and no error in technique can be established.

If, after all the above-mentioned precautions have been observed, the tracing still shows 60-cycle interference, the possibility of an electrical fault in the apparatus itself should be considered. In a direct-writing instrument this can easily be established by observation of the base line after the patient cable has been disconnected. Continued interference under such circumstances points to an intrinsic electrical defect.

Other types of electrical interference may occasionally be encountered and lead to confusion as they are characterized by a different frequency. Telephone bells, for example, have a frequency of 20 cps, while that of telephone dials is 5 cps. The pattern produced by the latter bears some resemblance to that of auricular flutter.

It should be emphasized that technically satisfactory tracings can as a rule be obtained in spite of the numerous possible sources of electrical interference, and neighboring electrical equipment may remain in use without necessarily introducing artifacts into the record.

Wandering of the Base Line. A temporary shift in the base line is a common occurrence and is usually confined to a portion of one or more leads. It is most commonly related to movements of the patient resulting from either restlessness or an uncomfortable position (Fig. 4-2E). Another possi-

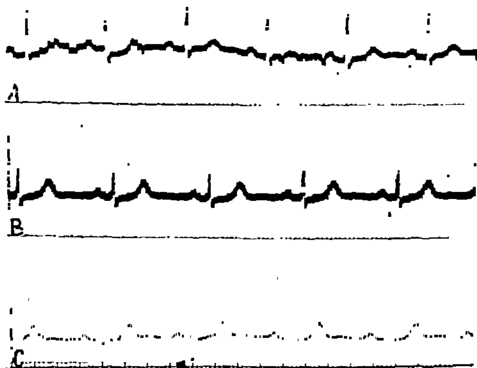


Fig. 4-3. A. Artifact associated with a loose lead wire on one extremity. B. Stylus temperature too high. The base line is too thick, and small deflections may thus be obscured. C. Stylus temperature too low. The tracing has a grayish appearance, and the complexes are indistinct.

rises more slowly to its summit and also descends more gradually. Overdamping is observed in tracings recorded with string galvanometers in the presence of high skin resistance. This factor necessitates undue loosening of the string if standardization is to be kept normal The complexes in such a record appear slurred and distorted.

Deflection Time. This is the time taken by the string, light beam, or stylus to reach the peak of its excursion from the base line. Inspection of the standardization wave should show a total deflection time of 0 02 sec or less. Eighty per cent of the final deflection must be attained within 0.01 sec in a critically damped machine. In direct-writing instruments, the deflection time varies between 0 006 and 0 01 sec, depending on the model. String galvanometers have an even shorter deflection time, but this value increases with increase in the skin resistance of the patient. The deflection time is therefore an index of the speed of response of a particular instrument and is related to the inertia of the mechanism In the string galvanometer the shadow maintains a constant deflection from the base line for as long a period as the standardization button is depressed In the amplifier type of instrument, however, this is not the case. Steady introduction of a current of 1 millivolt (1 mv) into the circuit produces the so-called *decay curve* (Fig 4-5).

This should be recorded as follows, with the paper drive (or camera) running, the calibration button should be depressed and held down until the curve falls to the base line At that instant the button is released, and a negative (downward) deflection will normally result, equaling the initial positive deflection in amplitude and duration When the curve again reaches the base line, several standardization waves should be recorded in rapid succession, that is, at a rate of three to four per second. Analysis of this curve will reveal the state of operational efficiency and integrity of the instrument Apart from the deflection time and degree of damping the following additional criteria of importance can be readily checked (1) Following the peak of the initial deflection, the curve should pursue a level ("plateau") course for at least 0.10 to 0 12 sec. (2) The next portion should show a smooth decline (decay) towards the base line. If the instrument is in good working order this decay time should measure at least 2 sec (Fig 4-5A). (3) The negative deflection should be compared with the positive curve (Fig. 4-5B). Normally the two are symmetrical. If they are not, there will be unequal amplification of positive and negative deflections in the electrocardiogram. (4) The series of standardization impulses recorded at a rate of three to four per second at the end of the curve should be of practically equal height in an instrument with an adequate frequency response (Fig. 4-5C).

Frequency Response. The electrocardiograph must yield a faithful record of the voltage variations of the heart. The component frequencies of the human electrocardiogram which are considered significant are of a comparatively low order, ranging from approximately 1 3 to 40 cps. Low-amplitude oscillations of higher frequency (40 to 70 cps) can sometimes be distinguished as fine notches in the QRS complex, but no diagnostic importance can be attached to them in the present state of medical knowledge

The frequency response of an electrocardiograph varies with the type of apparatus. In the interest of adequate recording fidelity, the *Council on Physical Medicine of the A.M.A.* has laid down certain minimum standards of acceptability, including the lower permissible limits of decrease in frequency response (expressed as a percentage). For example, an input voltage of 1 mv should produce an output response of 1 mv (10 mm deflection) if the standardization button is depressed once only. Repeated standardization at a rapid rate will result in a slight decrease in the amplitude of the deflections. At 15 cps, the decrease in frequency response must not exceed 10 per cent (9 mm deflection). At 40 cps, the loss in amplitude must not fall below 20 per cent (8 mm deflection). This progressive decrease in fre-

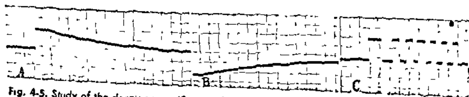


Fig. 4-5. Study of the decay curve. (See text.)

Arrest of such motion is obviously necessary if distortion of the tracing is to be avoided. In the string apparatus, damping is brought about simply by friction between string and air. The mirror galvanometer (oscillograph) is damped by suspension of the moving parts in oil of a suitable viscosity. In the direct-writing instruments, damping is partly magnetic and partly due to the friction between stylus and paper. Ideally, damping should be *critical*, that is to say, arrest of motion should coincide with cessation of current flow. If the instrument is critically damped, a brief depression of the calibration button will produce a sharp rectangular deflection. (Its amplitude will be 10 mm at normal standardization.) *Overshooting* (or underdamping) of a slight degree (1 mm or less) is permissible and is preferable to *overdamping* which is characterized by a generally blunted standardization deflection. It

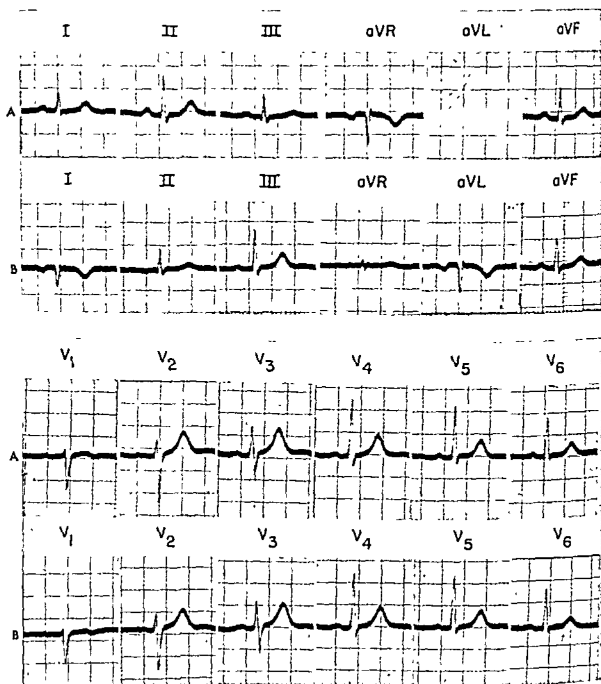


Fig. 4-4. Reversal of the lead wires to the right and left arms. A. Normal tracings with lead wires connected correctly. B. Lead wires reversed. Lead I is mirror image of itself. Leads II and III are transposed, as are aVR and aVL. The chest leads and aVF are not affected.

in the diagram, but it must be remembered that an infinite number of pathways exists in all three dimensions The greatest quantity of current flows along lines approximating the shortest distance between the two poles, but the current density diminishes as the lines increase in length. These lines represent the electrical field of the battery and are comparable to the electrical field of the heart in the body. Along each line of flux connecting the two poles, there is a progressive fall in potential. The shorter the line, the more rapid is the rate of fall in potential along its course, and vice versa Since the voltage at each pole is of the same magnitude but of opposite sign, and since the conducting medium is homogeneous, the midpoint on each line should be at zero potential, and this is in fact the case. If all these midpoints are joined, a straight line is obtained—the so-called *line of zero potential*—which also bisects the dipole axis at right angles. The electrical field is thus symmetrical with respect to this line, being divided into a positive and a negative half In three-dimensional terms, one can speak of a *plane of zero potential* which passes through all points of zero potential and is perpendicular to the direction of current flow. The curves joining all points of the same potential are known as the *isopotential lines* which are likewise perpendicular to the lines of flux (Fig 4-6). The diagram also illustrates another point of practical importance. It will be noted that there is little or no flow of current into the various appendages This means that throughout their entire length they exhibit much the same potential, its value being that of the region where the corresponding "limb" joins the "trunk" In other words, they behave as linear conductors which transmit potentials in one direction only—in this instance peripherally. This fact serves to explain the clinical observation that the size and configuration of the electrocardiographic complexes in the extremity leads is independent of the level at which the electrodes are applied to the limbs The potential variations in a limb are simply those existing at its root. The arms and legs therefore merely act as an extension of the lead wires, as it were

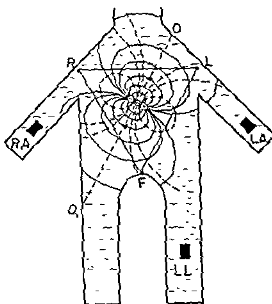


Fig. 4-6. Diagrammatic representation of the distribution of currents and potentials in a volume conductor An artificial dipole is created in the center of the main tank by means of two wires connected to the poles of a battery (not shown). The isopotential (interrupted) lines are everywhere perpendicular to the lines of current flow (solid lines); OO_1, line of zero potential; RA, right arm; LA, left arm; LL, left leg. The electrodes are represented by the solid rectangles See text. (Modified from Johnston, in Sodeman's Pathologic Physiology)

CLINICAL LEADS

As has already been indicated, clinical electrocardiography is *restricted* to the use of indirect or, in certain instances, semidirect leads. Leads may further be classified as bipolar, *semiunipolar*, and *unipolar*.

Bipolar Leads In this type of lead, the potential fluctuations at both electrodes are usually of the same magnitude but often opposite in sign. The outstanding examples are the *standard limb leads* I, II, and III, also known as the classical or *Einthoven leads* They held the field from the beginnings of clinical electrocardiography until the 1930s and are still recorded routinely, as they continue to prove their value and usefulness The limbs chosen for the application of the electrodes are the right and left arms and the left leg, although the right leg would serve equally well since the potential variations in both lower extremities are practically the same. By convention, *however*, the right leg carries the grounding electrode. The standard leads are easily reproducible, and serial tracings are strictly comparable, an advantage which is not possessed by the precordial *leads It should be* remembered that the potential variations in the left arm are in fact those presenting themselves *at the left shoulder*, the

quency response is due to the inertia of the moving parts of the galvanometer. Even though some of the higher-frequency components of the electrocardiogram tend to be minimized or suppressed, the frequency responses of direct-writing instruments are adequate for clinical work and their performance often exceeds the minimum requirements The newer models are also superior to the string galvanometer because, in the latter, the deflection time varies with the patient's skin resistance: as the resistance is increased the deflection time is increased and the frequency response is impaired

LEADS AND VOLUME CONDUCTORS

The contraction of cardiac muscle is immediately preceded by certain electrical events An essential part of these phenomena is the creation of potential differences in the heart which in turn give rise to electrical currents The heart muscle is surrounded by body fluids which, by virtue of their electrolyte content, act as *electrical conductors* In this manner, the cardiac currents flow through the conducting medium in all three dimensions and along an infinite number of pathways, the direction of flow being from the points of highest potential (positive or relatively positive) to those of lowest potential (negative or relatively negative) The point of highest potential has been called the *source*, that of lowest potential, the *sink* of the current. The body can, therefore, be regarded as *a volume conductor*, and as it may theoretically be considered able to conduct equally well in all directions, it is referred to as a *homogeneous volume conductor* (see Part 2, Chap. 5).

The application of this knowledge enables us to "pick up" the cardiac currents—or rather a fraction thereof—at the body surface This is done by means of an electrode from which the current is conducted to the galvanometer of the electrocardiograph via the lead wire, to be returned to the body by way of a second lead wire and its electrode The deflections registered by the galvanometer are proportional to the differences in potential existing between the two *points of electrode placement This* closed circuit is referred to as *a lead* The term "lead" is also used to denote the electrocardiographic record obtained as a result of any combination of electrode placements.

Leads may be classified according to the distance of the electrodes from the heart. Thus we speak of *direct, semidirect,* and *indirect leads.* In a *direct lead,* one or both electrodes are in direct contact with the myocardium, on either its epicardial or its endocardial aspect. These leads find application in experimental work with animals but are obviously impracticable in routine clinical electrocardiography where one has to rely chiefly on *indirect leads,* in which both electrodes are placed on parts of the body surface remote from the heart. *Semidirect leads* are intermediate in type in that one or both electrodes are situated in close proximity to the myocardium without being in actual contact with it. As will be pointed out later, *bipolar* and *unipolar leads* are also distinguished.

Two facts emerge from the foregoing: (1) two electrodes are always necessary for any given lead, irrespective of its type, (2) in all leads the operator measures potential differences between two selected points on (or in) the body by means of the galvanometer which is interposed in the external circuit.

For a better understanding of the distribution of currents and potentials in volume conductors, it is helpful to resort to a model which will approximately reproduce the situation encountered in clinical electrocardiography (Fig 4-6). The diagram shows a cylindrical tank which represents the trunk The upper and lower extremities are represented by four appendages in the appropriate locations and the whole model is filled with physiologic saline solution. Two wires are suspended in the center of the tank a very short distance apart. One of these is connected to the positive pole of a small battery, the other to the negative pole This arrangement can be regarded as the equivalent of the heart. The tank constitutes a homogeneous volume conductor. As it is very large in comparison to the short distance between the ends of the two wires, it may be considered to be of infinite size. The tips of the two wires form a *dipole* or *doublet,* by which is meant two electrical charges of equal magnitude but opposite sign, in close proximity *to each other The line drawn between* the two charges is known as the *dipole axis*

A flow of current occurs from the positive to the negative pole via the conducting medium Some of the lines of current flow are indicated

4. The heart is comparable to a small battery or dipole. To put it another way, the sum of the electromotive forces produced by the heart at any instant during the cardiac cycle is equivalent to a single dipole which is situated at the center of the heart.

Some of these postulates will be discussed in more detail in relation to the electrical axis. Einthoven's concept of the heart as a dipole is based on the application of an electrical theorem by which it can also be proved that, at any instant in the cardiac cycle, *the algebraic sum of the potentials at the right arm, left arm, and left leg is equal to zero.* Thus,

$$VR + VL + VF = 0$$

This fact is of importance for the understanding of the "indifferent" electrode employed in the recording of unipolar leads In fact, Einthoven's triangle is by no means equilateral, the body is not spherical, and the various tissues differ in their conductivity. Moreover, the heart is eccentric in position The validity of these concepts has therefore been called into question, but as they represent a sufficient approximation to the truth, they have stood the test of time and outlived the criticisms leveled against them

Each of the three extremities used in the standard bipolar leads plays a part in two of these leads For instance, the left arm participates in leads I and III It may therefore be postulated that a mathematical relationship should exist among the three leads.

$$I = VL - VR \qquad II = VF - VR$$
$$III = VF - VL$$

Adding leads I and III yields the following·

$$I + III = VL - VR + VF - VL$$

Therefore

$$I + III = VF - VR$$

and therefore

$$I + III = II$$

The algebraic sum of the potentials of lead I and those of lead III thus equals the potentials of lead II This relationship is known as *Einthoven's law* and holds true for leads from any three points In other words, the potential difference between two points on the body is equal to the algebraic sum of the potential differences between each of these points and a third point. This principle applies to any three sites exhibiting a difference in a chosen scalar quantity, such as height, temperature, etc. Although the standard leads are valuable, they frequently do not reflect pathological changes in the myocardium which may be clinically obvious. The explanation for this lies in the fact that the axes of the standard leads lie in the frontal plane and can thus only record electrical forces which lie either in this plane or can be projected onto it. This realization led to the search for methods of recording along different axes.

Semiunipolar Leads. In this type of lead, one electrode is placed close to the heart while the other is located over an area distant from the source of the cardiac currents. The former is termed the *exploring*, the latter the *semiindifferent electrode* The potential variations at the exploring (positive) electrode are therefore large, while those at the semiindifferent (negative) electrode are comparatively small but not negligible These leads are no longer in use today but are included here for the sake of completeness The following combinations were used. CF_4, CR_4, CL_4, and CB_4 (lead IV). Of these, CF_4 was the lead most commonly employed. The letter C in each case referred to the exploring electrode on the chest wall, the subscript 4 denoting its exact position, i e., over the 5th intercostal space in the left midclavicular line. The letters F, R, L, and B indicated the position of the semiindifferent electrode on the left leg, right arm, left arm, and back (near the angle of the scapula) respectively. CB_4 would be, therefore, an anteroposterior lead.

Unipolar Leads These comprise both the unipolar limb or extremity leads and the unipolar chest or precordial leads (See Unipolar Electrocardiography, p. 45)

Position of the Electrodes in the Precordial Leads. These are also referred to as *V leads* (designating voltage). The exploring (positive) electrode is placed over certain points on the chest wall in succession, while the central terminal again serves as the indifferent electrode. Each chest lead is designated by a subscript numeral which indicates the position of the exploring electrode (Fig. 4-8). The following are the leads in either frequent or routine use (the anatomical landmarks given indicate the site of placement of the exploring electrode)

Lead V_1 4th intercostal space at the right sternal border
Lead V_2: 4th intercostal space at the left sternal border
Lead V_3· in a position midway between V_2 and V_4
Lead V_4. in the left midclavicular line, 5th intercostal space
Lead V_5· left anterior axillary line, level with V_4
Lead V_6. left midaxillary line, level with V_4 and V_5
Lead V_7· left posterior axillary line, level with V_6

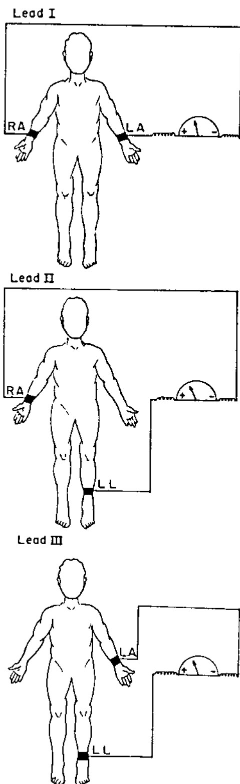


Fig. 4-7. The standard lead connections, as introduced by Einthoven. With this arrangement, positivity at the left arm electrode with respect to the right arm electrode will result in an upright deflection in lead I. Similarly, positivity at the left leg electrode in relation to the right and left arm electrodes will give rise to upright deflections in leads II and III respectively.

same is true for the right arm in relation to *the right shoulder* and for the left leg as regards *the left hip* (or pubic symphysis). In lead I, the left and right arms are connected to the galvanometer, the former to its positive, the latter to its negative pole. Lead II involves the right arm and left leg, the electrode on the left leg is connected to the positive, that on the right arm to the negative pole of the recording instrument. Lead III concerns the left leg and left arm; the left leg electrode is connected to the positive terminal, and the left arm electrode to the negative terminal. This arbitrary system was introduced by Einthoven who discovered that if the connections were made in this manner the main deflections in all three leads were upright in the majority of normal subjects (Fig. 4-7). Therefore,

Lead I records the difference in potential between the left arm and the right arm:

$$I = L.A. - R.A.$$

Lead II records the difference in potential between the left leg and the right arm:

$$II = L.L. - R.A.$$

Lead III records the difference in potential between the left leg and the left arm:

$$III = L.L. - L.A.$$

If the symbol V is used to denote potential, these equations can be written as follows.

$$I = VL - VR \qquad II = VF - VR$$
$$III = VF - VL$$

The symbols R, L, and F refer to the right arm, left arm, and left leg respectively. Therefore this is a matter of potential differences involving three points, namely, the right and left shoulders and the left hip. An imaginary line drawn between the two shoulders constitutes the axis of lead I, while similar [illegible] and left [illegible] II and I[illegible] sides of what is known as *Einthoven's triangle.* Certain important concepts were first formulated by Einthoven (1913) and are known as the *Einthoven triangle hypothesis* They are based on the following assumptions.

1 The body is a spherical homogeneous volume conductor of infinite size

2 The heart is situated at the center of the body and of the triangle.

3 The roots of the three limbs used in the standard leads form the apices of an equilateral triangle lying in the frontal plane of the body. Therefore, the electrodes are considered to be equidistant from one another and also from the center of the heart.

4 The heart is comparable to a small battery or dipole. *To put it another way, the sum of the electromotive forces produced by the heart at any instant during the cardiac cycle is equivalent to a single dipole which is situated at the center of the heart.*

Some of these postulates will be discussed in more detail in relation to the electrical axis. Einthoven's concept of the heart as a dipole is based on the application of an electrical theorem by which it can also be proved that, at any instant in the cardiac cycle, *the algebraic sum of the potentials at the right arm, left arm, and left leg is equal to zero.* Thus,

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This fact is of importance for the understanding of the "indifferent" electrode employed in the recording of unipolar leads. In fact, Einthoven's triangle is by no means equilateral, the body is not spherical, and the various tissues differ in their conductivity. Moreover, the heart is eccentric in position. The validity of these concepts has therefore been called into question, but as they represent a sufficient approximation to the truth, they have stood the test of time and outlived the criticisms leveled against them.

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The explanation for this lies in the fact that the axes of the standard leads lie in the frontal plane and can thus only record electrical forces which *lie either in this plane or can be projected onto it.* This realization led to the search for methods of recording along different axes.

Semiunipolar Leads. In this type of lead, one electrode is placed close to the heart while the other is located over an area distant from the source of the cardiac currents. The former is termed the *exploring*, the latter the *semiindifferent electrode.* The potential variations at the exploring (positive) electrode are therefore large, while those at the semiindifferent (negative) electrode are comparatively small but not negligible. These leads are no longer in use today but are included here for the sake of completeness. The following combinations were used. CF_4, CR_4, CL_4, and CB_4 (lead IV). Of these, CF_4 was the lead most commonly employed. The letter C in each case referred *to the exploring electrode on the chest wall*, the subscript 4 denoting its exact position, i.e., over *the 5th intercostal space in the left mid-*clavicular line. The letters F, R, L, and B indicated the position of the semiindifferent electrode on the left leg, right arm, left arm, and back (near the angle of the scapula) respectively. CB_4 would be, therefore, an anteroposterior lead.

Unipolar Leads. These comprise both the unipolar limb or extremity leads and the unipolar chest or precordial leads. (See Unipolar Electrocar-

[illegible] ***Precordial***

Leads. [illegible] *eads* (designating voltage). The exploring (positive) electrode is placed over certain points on the chest wall in succession, while the central terminal again serves as the indifferent electrode. Each chest lead is designated by a subscript numeral which indicates *the position of the exploring electrode* (Fig. 4-8). The following are the leads in either *frequent or routine use (the anatomical landmarks* given indicate the site of placement of the *exploring electrode*).

- Lead V_1: 4th intercostal space at the right sternal border
- Lead V_2: 4th intercostal space at the left sternal border
- Lead V_3: in a position midway between V_2 and V_4
- Lead V_4: in the left midclavicular line, 5th intercostal space
- Lead V_5: left anterior axillary *line, level with* V_4
- Lead V_6: left midaxillary line, level *with* V_4 and V_5
- Lead V_7: left posterior axillary line, level with V_6

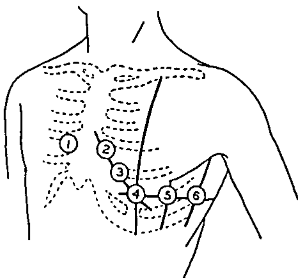


Fig. 4-8. Position of the "exploring electrode" for recording the chest leads.

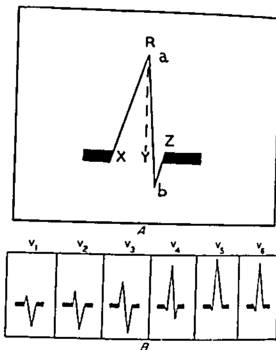


Fig. 4-9. A. The intrinsic deflection, line *ab*. The time elapsing before the onset of this deflection is represented by the interval *XY*. B. Normal transition in the configuration of the QRS complex as seen in the six routine precordial leads. (*From Lipman and Massie. Clinical Unipolar Electrocardiography, 1956*)

Lead V_8: over the inferior angle of the left scapula, i.e., level with the 7th thoracic vertebra

Lead VE: over the ensiform cartilage at the lower end of the sternum

Lead V_3R. a position over the right precordium corresponding to V_3

Lead V_4R: a position over the right precordium corresponding to V_4

Other sites are occasionally chosen to aid in the clarification of certain diagnostic problems For instance, placement of the exploring electrode one or even two interspaces *above* its usual position may provide confirmatory evidence in cases of suspected high lateral-wall myocardial infarction A lead taken one or two interspaces above the position of V_1 and recorded with double standardization may at times determine the presence or absence of P waves. Leads V_4R, V_5R, V_6R, etc., are of value occasionally Their subscripts indicate that they are right precordial leads with positions corresponding to those of V_4, V_5, V_6, etc. Leads V_1 through V_6 are now part of the routine electrocardiogram in adults

TERMINOLOGY

In normal, healthy individuals the initiating stimulus arises in a small nucleus of specialized myocardial fibers situated in the wall of the right atrium near the point of entry of the superior vena cava. It is known as the *sinoatrial node* (*SA node*) and is histologically distinct from the surrounding myocardium (Part 1, Chap. 5).

The rapid and steep downstroke beginning at the peak of R and ending at the nadir of S is referred to as the *intrinsic deflection* in direct epicardial leads and represents the arrival of the depolarization dipole in the muscle directly underlying the exploring electrode. The term *intrinsicoid deflection* is used in clinical electrocardiography in connection with the precordial leads and corresponds to the intrinsic deflection. The time of onset of the intrinsic(oid) deflection (or ventricular activation time) is considered to be of diagnostic importance in certain conditions. It is measured along the base line from the beginning of the first component of QRS to a point at which a perpendicular dropped from the peak of the R wave intersects the isoelectric line (Fig 4-9).

If the exploring electrode is placed over the point of stimulation, the entire deflection will be negative. Its descending limb is steep and rapidly reaches its nadir since the electrode immediately faces the "sink" of the current As the activation wave moves distally, the influence of the negative field gradually diminishes, and the ascending limb slopes back towards the base line which is reached on completion of the depolarization process.

During depolarization, the positive pole precedes the negative pole while the reverse holds true during repolarization. These two processes together constitute *electrical systole*.

THE COMPONENTS OF THE ELECTROCARDIOGRAM

The characteristic deflections representing the various electrical events already described, normally occur in a definite sequence and were designated arbitrarily P, Q, R, S, and T by Einthoven (Fig. 4-10).

The *P wave* is inscribed during atrial depolarization and is also referred to as the *atrial (auricular) complex*. The discharge of the SA node cannot be recorded by conventional clinical means but is thought to slightly precede the onset of the P wave. The P wave is followed by the *P-R segment*, which is normally short and sometimes shows a slight slope. Its inscription marks the passage of the activation process through the AV node, the bundle of His, its branches, and the Purkinje network. Ventricular depolarization follows, commencing with septal activation from left to right. It is represented by the rapidly inscribed *QRS complex*. This terminology is applied to this complex by convention although any one, or even two, of its three components, may normally be absent. If the initial deflection is downward, it is labeled Q. The first upward deflection, whether preceded by a Q wave or not, is called the *R wave*. Any downward deflection following R is designated as S. The actual configuration of this component of the

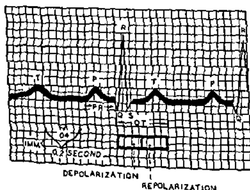


Fig. 4-10. Diagrammatic representation of the more important components of the normal electrocardiogram. (From Lipman and Massie, Clinical Unipolar Electrocardiography, 1956.)



Fig. 4-11. Commonly encountered variations in the configuration of the QRS complex.

electrocardiogram varies considerably in different leads. The commoner combinations may be expressed by appropriate symbols, such as R, qR, RS, Rs, qRs, QS (Fig. 4-11), capital and small letters being used to indicate the relative sizes of the various deflections. A second positive deflection sometimes follows the S wave. This is designated as R' or r' (R prime). Any negative deflection following R' is similarly called S' or s'. Possible subsequent waves are denoted by the symbols r" or s", and so forth.

The QRS complex is followed by a usually isoelectric period of varying duration, known as the *S-T segment*. It begins at the point at which the last deflection of QRS returns to the base line and ends with the beginning of the T wave. The *T wave represents ventricular repolarization* and is more slowly inscribed than the QRS complex. Not infrequently the T wave is followed by a separate shallow deflection known as the *U wave*, which normally points in the same direction as the T wave with which it is associated. On occasions, the U wave may be very prominent, especially in the right and midprecordial leads. In other leads, it is often partially or completely fused with the T wave. The significance of the U wave is uncertain. It has been stated that it represents repolarization of the papillary muscles and other related structures, while other views have been discussed by Lepeschkin.

Atrial repolarization gives rise to a small deflection known as the Ta or Tp wave which follows P and is opposite in sign to it. It is rarely seen in normal tracings, as it is usually concealed by the QRS complex, but may be revealed in cases with prolonged AV conduction or complete heart block. It is of some importance in the presence of tachycardia as it may produce S-T-segment depression which could be erroneously interpreted. It is also responsible for the slight slant of the P-R segment noted above.

THE NORMAL ADULT ELECTROCARDIOGRAM

Heart Rate. Normally the SA node is the dominant cardiac pacemaker and therefore determines the heart rate. Under these conditions, a rate between 60 and 100 beats per minute constitutes *normal sinus rhythm.* If the rate exceeds 100 per minute *sinus tachycardia* is mentioned; if it falls below 60 per minute *sinus bradycardia* is said to be present. These terms are merely relative since a resting rate of 90 per minute represents tachycardia in an individual whose usual rate under the same conditions is known to be only 60 per min. However, these limits have been agreed upon for the sake of convenience and in the interests of standardization of electrocardiographic nomenclature.

Calculation of the Heart Rate. The electrocardiographic paper used in direct-writing machines has vertical time-lines which are 1 mm apart. Every fifth line is bolder than the rest, and the distance between any two of these equals 5 mm. As the paper speed is normally 25 mm/sec, the distance between two adjacent thin lines corresponds to 0.04 sec, and that between two heavy lines to 0.20 sec. In the photographic type of instruments, the intervals between the thin and thick time-lines have the same values.

With this knowledge, calculation of the heart rate becomes a matter of simple arithmetic, provided the rhythm is regular. The heavy time-lines appear at the rate of 5 per second, or 300 per minute, while the number of thin lines is 25 per second or 1,500 per minute. The rate can thus be obtained by one of two methods: (1) counting the number of the 0.04-sec intervals lying between a chosen point on one particular deflection and the corresponding point on the same wave in the next cycle, or (2) counting the number of 0.20-sec intervals in the same manner. For the determination of the ventricular rate, the peak of the R wave or the nadir of the Q wave, if well-defined, are the most suitable reference points. The R-R interval (or P-P interval) is referred to as the *cycle length.* The respective formulas are

$$\text{Rate per min} = \frac{1{,}500}{\left\{\begin{array}{c}\text{no. of 0.04-sec intervals be-}\\ \text{tween 2 adjacent cycles}\end{array}\right\}} \quad (1)$$

$$\text{Rate per min} = \frac{300}{\left\{\begin{array}{c}\text{no. of 0.20-sec intervals be-}\\ \text{tween 2 adjacent cycles}\end{array}\right\}} \quad (2)$$

Some types of electrocardiographic paper have vertical linear time markings at 3-sec intervals along their margins. By counting the number of complexes occurring in a lead over a 6-sec period and multiplying by ten, the approximate rate can be rapidly obtained, and this value is usually adequate for most clinical purposes. This method can also be applied to irregular rhythms. In atrial fibrillation, however, the ventricular rate may vary so widely from instant to instant that the average of several leads should be taken.

Intervals. P-R INTERVAL (OR P-Q INTERVAL). This interval covers the period of time from the beginning of atrial depolarization to the onset of ventricular depolarization and is accordingly measured from the beginning of the P wave to the point at which the first component of the QRS complex leaves the base line. The P-R interval must be measured routinely in the interpretation of a tracing as it furnishes important information concerning the state of AV conduction. Lead II is usually chosen for this purpose, provided the deflections are well defined and their origins clear-cut. As this method may be subject to error, *it has been suggested that the longest P-R interval found in the standard or unipolar extremity leads should be selected instead.* This is not necessarily the true P-R interval, but since it does not differ from the latter by more than 0.01 sec, it is sufficiently accurate to be acceptable.

The upper limit of normal values for adults is 0.20 sec; for adolescents between 14 and 17 years, 0.18 sec; and for children under 14 years, 0.16 sec. The P-R interval thus tends to lengthen with advancing age. It also shortens to some extent as the heart rate increases. A small percentage of healthy individuals show durations of 0.21 or 0.22 sec or more, but the majority of subjects exhibiting prolonged AV conduction have heart disease of one type or another. The lower limit of normal values is considered to be 0.12 sec, but here again exceptions have been noted among normal individuals.

QRS INTERVAL. Measurement of the duration of the QRS complex discloses the intraventricular conduction time. For this purpose, the widest complex should be selected from among the six limb leads. The upper limit of normal values is 0.10 sec for adults, 0.09 sec for children between the ages of 5 and 14 years, and 0.08 sec for children under 5 years of age. The lowest limit of normal values has not been defined

although it is rarely less than 0.06 sec. The *QRS interval* therefore again varies directly with age. On the other hand, considerable increases in rate result in only a slight shortening of the interval. It should be noted that the maximum QRS interval duration is usually somewhat longer in the precordial *leads. In a* small percentage of normal persons intraventricular conduction has been found to be prolonged to 0.11 or 0.12 sec. However, cardiac disease is responsible for the majority of cases showing such great increases of the QRS interval

Q-T INTERVAL. This represents the time necessary for electrical systole and is measured from the beginning of the first component of the QRS complex to the termination of the T wave. There are several possible sources of error in the measurement of this interval, such as fusion of the T and U waves or superimposition of the P and T deflections in cases with marked tachycardia. Since U waves usually appear as separate deflections in the right or midprecordial leads, *the first* difficulty may be overcome by *choosing such* a lead for the determination of the interval In the second case the problem may not be amenable to solution unless simultaneous leads can be recorded In arrhythmias, *such as* atrial fibrillation or extrasystoles, the Q-T *interval varies*, and the average value should therefore be determined from a measurement of a number of Q-T intervals. Prolongation of intraventricular conduction also lengthens electrical systole, but the *necessary* correction can be made from tables by using the expected duration of the QRS *complex for* the age and heart rate of the patient.

For maximum accuracy the longest Q-T interval found in any of the available leads should be selected for the calculation As the interval varies inversely with the cardiac rate, a correction for the latter must be made. This can be done by using *Bazett's formula*, modified by Taran and Szilagyi.

$$Q\text{-}T_c = \frac{Q\text{-}T\ (\text{actual})}{\sqrt{\text{cycle length}}}$$

$Q\text{-}T_c$ = the Q-T interval corrected for rate

The results can also be read off directly from specially prepared tables. In view of the many possible errors inherent in the measurement of the Q-T interval, it has been suggested that its upper limit of normal values, regardless of age or sex, should be 0.425 sec.

Q-R INTERVAL. This is measured from the beginning of the QRS complex to the peak of the [illegible] which as already stated, marks the [illegible]

tion time If an RSR'S' configuration is [illegible], the larger of the two downstrokes should be regarded as the true intrinsicoid deflection

The peak of R indicates the beginning of the activation process in the epicardium under the electrode while the nadir of the S wave represents its completion. The Q-S interval would therefore more accurately reflect the actual time required for depolarization but, for practical reasons, the Q-R interval is preferred *Over the right precordium*, the upper limit of normal values is considered to be 0.03 sec, while the *corresponding* value *over the left precordium* lies between 0.05 and 0.06 sec. Several authors consider that lengthening of the *Q-R interval over* either the right or the left side of the precordium indicates *respectively* hypertrophy of the *right or the left* ventricle Others do not accept this as a diagnostic criterion of ventricular hypertrophy in view of the inertia of the electrocardiograph and for other technical reasons.

Deflections. The amplitude of the various waves has to be measured from a well-defined reference level. A committee of the *American Heart Association* recommended (1943) that *two separate* reference levels be used for this *purpose The T-P (or U-P) interval normally is the isoelectric level* and should be used as the base line for the P wave, Ta wave, S-T segment, T wave, and U wave. The *remaining* components of the cardiac cycle, namely, Q, R, and S, as well as the *RS-T junction ("J")*, should be assessed in relation to the preceding *P-R segment* This is explained by the fact that the Ta wave is usually superimposed both on that segment and on the QRS complex A new base line is therefore established for any deflections occurring during atrial repolarization. This becomes important in patients with tachycardia in whom the increase in size of the Ta [illegible]

[illegible] no general agreement as to the normal range of amplitude for the various deflections, and the different criteria laid down are therefore somewhat arbitrary.

P WAVE. Its amplitude should not exceed 3 mm (0.3 mv) in height in leads I, II, or III. In most normal subjects it is considerably less. Its height in any of the augmented unipolar limb or precordial leads should not be greater than 2.5 mm. Values larger than those quoted above constitute high voltage, while low voltage is characterized by P waves measuring less than 0.5 mm in *all leads*. The normal P wave has a maximum duration of 0.10 sec as measured in the six extremity leads, but some authorities consider 0.11 sec the upper limit of normal values. Measurement of its width is made along the base line from the inner border of its ascending limb to that of its downstroke.

QRS COMPLEX. The amplitude of any upward deflection is represented by the vertical distance between the upper border of the termination of the P-R segment and the point level with the upper edge of the peak of that deflection. The voltage of a downward deflection is obtained by measuring the vertical distance between the lower border of the P-R segment at its termination and the point level with the lower edge of the nadir of that deflection. *High voltage* is said to be present under these conditions of measurement if the largest component of the QRS complex exceeds 25 mm (2.5 mv) in one of the standard leads, *or* 20 mm in one of the augmented unipolar limb leads, *or* 50 mm in one of the precordial leads. High voltage unaccompanied by other electrocardiographic changes may be due to a number of factors, both physiological and pathological, and care in its interpretation is therefore necessary. *Low voltage* is considered to be present if the largest deflection of QRS does not attain an amplitude of 5 mm (0.5 mv) in any of the six extremity leads and is less than 10 mm (1.0 mv) in *all* six precordial leads. Low voltage in the limb leads only is not necessarily of pathological significance and is sometimes seen in obese subjects. The limits of "normal" values have thus been defined, but it should be borne in mind that different authorities have proposed different criteria which are equally arbitrary.

Q WAVE. The *normal Q wave* should not exceed 0.04 sec in duration but may have pathological import even at 0.03 sec or less, depending on a number of factors, such as its depth relative to the height of the R wave in the same or in other leads, and the actual lead or leads in which it is found. The preceding criteria for width do not apply to pure QS complexes.

THE RS-T JUNCTION (OR "J"). This is the point of sudden transition in the tracing from the abrupt slope of the QRS complex to the gentle slope of the RS-T segment. "J" therefore indicates the end of QRS. Displacement of the RS-T junction in either direction may be diagnostically important and is assessed in relation to the end of the P-R segment for the reasons already stated. Slight degrees of either elevation or depression are not significant but should not exceed 1 mm (0.1 mv) in the standard leads. In the precordial leads, particularly those from the right side, elevations up to 2 mm (0.2 mv) are considered physiological and are in fact frequently observed. Depression of "J" in the chest leads should not exceed 1 mm (0.1 mv). In normal subjects, "J" tends to be displaced in the direction of the T wave; the taller the latter, the more pronounced the displacement becomes.

S-T SEGMENT. This segment is the portion of the tracing lying between the RS-T junction and the beginning of the T wave. In many cases it is horizontal, which indicates that ventricular depolarization is complete and that repolarization has not yet begun. Frequently, however, it takes the form of a gentle slope which is evidence that early repolarization forces have encroached on the segment. It therefore belongs to the recovery phase of the cycle and represents the earliest and major portion of the T complex. If the slope of the segment becomes steep enough, it may be impossible to distinguish between its point of termination and the onset of the T wave proper.

T WAVE. The normal T wave is slightly asymmetrical, having a relatively slow upstroke followed by a steeper and more rapid downstroke so that its summit lies closer to its termination than to its origin. It is normally upright but may be diphasic or even inverted in certain leads. *High voltage* is present if its amplitude (measured in one direction from the reference level) is greater than 7 mm (0.7 mv) in leads I, II, or III, *or* exceeds 5 mm in any of the aV leads, *or* 20 mm in any of the precordial leads. *Low voltage* is said to exist if the T wave is less than 1 mm (0.1 mv) tall in *all* the limb leads and does not attain an amplitude of 2 mm in any of the routine precordial leads.

TABLE 4-1 ELECTROCARDIOGRAPHIC DEFLECTIONS IN NORMAL ADULTS, TWENTY YEARS AND OVER, IN TENTHS OF A MILLIVOLT

Lead	P				Q				R				S				RS or QR				S-T				T			
	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean	No Cases	Min	Max	Mean
I	475	0	2.5	0.69	505	0	2.0	0.27	505	0.7	19.4	5.51	505	0	6.4	1.27	63	3.0	20.6	8.54	100	−0.3	0.9	0.11	505	−0.5	5.6	2.20
II	475	0	3.0	1.07	505	0	4.0	0.38	505	0.5	28.0	9.41	505	0	8.2	1.36	63	8.0	32.0	15.14	100	−1.0	1.0	0.21	505	0	8.0	2.67
III	475	−0.8	2.0	0.56	505	0	4.0	0.48	505	0	22.0	5.56	505	0	13.0	1.29	63	3.2	25.0	10.62	100	−0.6	0.8	0.04	505	−2.0	5.5	0.77
VR	32	−1.0	−0.5	−0.63	62	0	8.0	2.48	62	0	3.0	0.90	62	0	11.0	3.01	62	3.5	12.0	6.50	32	0	0	0	62	−4.0	−0.5	−1.65
VL	32	−0.5	0.5	0.07	62	0	1.5	0.16	62	0	7.0	1.21	62	0	7.0	2.04	62	0.5	8.5	3.37	32	0	0	0	62	−1.0	1.5	0.29
VF	32	0	2.0	0.72	62	0	2.0	0.30	62	0	15.0	6.82	62	0	6.5	0.74	62	3.5	16.5	7.77	32	0	0	0	62	0	4.6	1.40
aVR	411	−1.5	−0.1	−0.79	552	0	16.8	2.38	552	0	4.1	0.94	552	0	15.7	3.76	—	—	—	—	—	—	—	—	479	−5.5	−0.2	−2.40
aVL	411	−1.0	1.4	0.51	552	0	3.5	0.27	552	0	10.1	2.61	552	0	11.3	1.35	—	—	—	—	—	—	—	—	479	−4.0	6.0	0.78
aVF	411	−1.8	1.7	0.74	552	0	3.0	0.38	552	0	20.0	4.73	552	0	7.1	0.81	—	—	—	—	—	—	—	—	479	−0.6	5.2	1.85
V_1	371	−1.1	2.2	0.57	567	0	0	0	567	0	15.5	3.09	567	0.8	26.2	9.44	63	6.6	35.0	14.99	33	0	0.5	0.01	542	−4.0	12.2	0.84
V_2	371	−0.7	2.0	0.60	504	0	0	0	594	0	23.0	5.96	594	0	39.2	14.09	63	13.0	55.0	26.82	33	0	1.0	0.09	542	−2.6	18.0	4.70
V_3	371	−0.5	2.0	0.61	567	0	1.5	0.01	567	0.7	54.6	8.93	567	0	57.5	9.51	63	11.1	54.6	24.12	33	0	2.0	0.20	542	−2.0	21.0	5.16
V_4	371	−0.2	2.3	0.60	594	0	4.0	0.13	594	1.8	46.0	13.78	594	0	28.8	5.93	63	9.0	51.6	26.10	33	0	1.0	0.03	542	−0.5	17.0	5.06
V_5	371	0	2.4	0.56	567	0	3.4	0.43	567	0.4	33.6	12.01	567	0	16.1	1.96	63	10.0	36.4	19.31	33	0	0	0	542	0	11.0	3.83
V_6	371	0	1.8	0.54	564	0	2.7	0.44	564	2.0	22.6	9.69	564	0	14.3	1.00	33	7.0	24.5	13.93	33	0	0	0	512	0	6.9	2.80
VE*	—	—	—	—	30	0	0	0	30	2.0	12.8	5.81	30	0	10.2	6.09	30	5.6	24.2	11.91	—	—	—	—	30	0.2	5.2	2.55

* VE lead from tip of ensiform cartilage

SOURCE From "Nomenclature and Criteria," 1953 Courtesy of the New York Heart Association

See Table 4-1 for the range of normal deflections based on the findings of several groups of investigators.

THE ELECTRICAL AXIS

Reference has previously been made to Einthoven's theory. As it has an important bearing on determination of the electrical axis, some of the salient concepts of this theory will be taken up in greater detail.

1. *The sum or resultant of the electromotive forces produced by the heart at any particular instant during the cardiac cycle is equivalent to a single dipole.* It has already been explained that such a force can be expressed symbolically as a *vector* which has a definite magnitude, direction, and sense. This vector is known as the *instantaneous electrical axis* and is itself the resultant of many smaller forces active at that moment. It changes in both magnitude and direction from instant to instant. If, for example, the positive termini of a large number of the instantaneous vectors of ventricular depolarization were to be joined by a continuous line, one would obtain a three-dimensional loop which is referred to as the spatial QRS loop. Reference is likewise made to P and T loops. The resultant of all the instantaneous vectors for any particular activation or recovery process is called the *mean electrical axis*. As a rule, this term refers to the mean QRS axis since the chief concern is with ventricular depolarization.

The apexes of the triangle formed by the roots of the three extremities may be regarded as remote from the dipole center when compared to the close proximity of the two charges of the dipole. The area of the triangle can thus be considered to be infinitely large, and the body of infinite extent The limb electrodes are distant from the heart, and under these conditions the concept of the heart as a dipole is entirely valid.

2. *The midpoint on the axis of the dipole of depolarization at any given moment constitutes the instantaneous electrical center of the heart, which is therefore at zero potential* As the instantaneous vectors change from moment to moment, the electrical center will also tend to migrate The mean electrical center of the heart is situated at the midpoint of the axis of the dipole represented by the mean vector.[2]

Einthoven further postulated that the electrical center of the heart is situated at the center of the equilateral triangle so that its apexes are not only distant but also equidistant from the dipole center. This concept retains its validity even though the triangle is not anatomically equilateral because the limb electrodes are remote from the cardiac dipole.

3. According to Einthoven's theory, *the body forms a homogeneous conducting medium*. Much criticism has been leveled at this postulate as it has been shown that different tissues display a marked difference in conductivity. The resistance of the lungs, for instance, is high whereas that of blood is relatively low. These factors tend to distort the electrical field of the heart.

It should be clear from the foregoing discussion that the mean electrical axis, whether it be that of atrial or ventricular depolarization or of ventricular repolarization, is a three-dimensional vector, of which the magnitude and orientation in space varies within certain limits even in normal subjects. It is probable that Einthoven formulated his hypothesis for the purpose of attempting to distinguish between normal and abnormal rotations of the QRS axis. It is this axis which will be referred to in the following paragraphs. In the majority of cases the mean axis is also the longest axis, that is to say, its magnitude exceeds that of any of its component instantaneous vectors. Its magnitude and direction are an index of the average intensity and pathway of ventricular activation.

Any of the spatial vectors can be projected onto the frontal plane which is also the plane of Einthoven's triangle, in practice, however, the mean electrical axis is selected as it is much more useful diagnostically. The frontal projection of this spatial vector is known as the *mean manifest electrical axis of ventricular activation* and is designated by the symbol $\hat{A}QRS$ [3]

The term *manifest* implies the planar projection of a three-dimensional quantity. By the same token, the projections of the mean mani-

[2] According to certain investigations, the mean electrical center for ventricular activation and recovery is believed to be located in the chest at the level of the 4th intercostal space and slightly to the left of the midsternal line.

[3] The symbol ^ (circumflex) indicates that one is dealing with a vector quantity; the letter A represents the area of the deflection.

fest *P* and *T* axes can be represented by the symbols ÂP and ÂT respectively.

If the mean manifest QRS axis is known (as derived, for instance, from a frontal plane vectorcardiogram), it can be represented vectorially in Einthoven's triangle (Fig. 4-12A). Its origin is at the center of the triangle while its free end is indicated by the tip of the arrow. By dropping perpendiculars to the sides of the triangle, the vector will be projected onto each of the three lead axes. It can be proved trigonometrically that the voltage recorded in any one of the standard leads is proportional to the projection of the mean vector on the lead axis concerned, provided the triangle is equilateral.

In lead I, the left arm is regarded as positive with regard to the right arm, while the left leg is positive in relation to both the right and left arms in leads II and III, respectively (Figs. 4-12A and 4-14A). These polarities are in conformity with the arbitrary system adopted by Einthoven. The midpoint on each side of the triangle is at zero potential and marks the boundary between the positive and negative half of the respective lead line (Fig 4-12A). As viewed by the reader, the right half of the axis of lead I is therefore positive while the left half is negative. Similarly, the lower halves of the axes of leads II and III are positive and the upper halves negative. The center of the triangle (*O*) corresponds to the electrical center of the heart If a line is drawn from O to each of the apexes the medians *OR*, *OL*, and *OF* represent the lead axes of the three unipolar limb leads This is explained by the fact that the negative electrode is formed by the central terminal; since this is at zero potential, it may be represented as lying at the center of the triangle. The medians *OR*, *OL*, and *OF* form the positive portions of these leads while their extensions beyond O may be regarded as negative. Each of these lead lines forms an angle of 60° with its neighbor, as is the case with regard to the standard lead axes (Fig. 4-12B).

The position of the mean manifest axis is expressed in terms of the angle it makes with the horizontal. For this purpose, a line *XY* parallel to lead *I* is drawn through the center of the triangle (Fig 4-13). Point *Y* represents 0° and point *X*, 180°. By convention, all angles below the *XY* axis are given *positive* values while all those above it are assigned *negative* ones. The degrees are conveniently marked off on a circle in either direction from the 0° point (Fig. 4-13). Point *X* may be either plus or minus 180° depending on the direction from which it is approached.

Determination of the Mean Manifest QRS Axis. This can be done with the aid of the standard leads. Any two of these can be used, but most commonly leads *I* and *III*. The initial step involves the determination of the net area enclosed by the QRS complex in the two leads selected This is done by first calculating the area bounded by each of the component deflections of QRS. Upward deflections are given a positive sign, downward excursions a negative sign The net area is obtained by algebraic summation of the various positive and negative areas. These are all expressed in microvolt-seconds. On conventional electrocardiographic paper the distance between two adja-

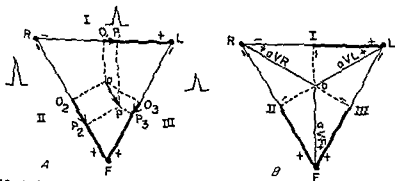


Fig. 4-12. A. Einthoven's triangle, showing the positive and negative half of each lead line. The vector, *OP*, has its origin at the center, O, of the triangle. Its projections on leads *I*, *II*, and *III* are represented by the segments O_1P_1, O_2P_2 and O_3P_3 respectively. This position of the mean axis is encountered in the "average normal" individual. The resultant deflections are upright (positive) in the three leads. B. Einthoven's triangle, showing the relationship between the bipolar and unipolar limb lead axes.

cent vertical time-lines represents 0.04 sec, while each millimeter between two horizontal lines is equivalent to 100 μv (0.1 mv). Each "small square" therefore equals 4 μv-sec or 1 *Ashman unit.*

To quote an example, lead I may show a qR configuration and lead II an rS complex. Suppose that in lead I

q = 2 μv-sec and R = 10 μv-sec,

in lead III,

r = 2 μv-sec and S = 8 μv-sec

The net area of the QRS complex in lead I will equal

$$(-2) + (+10) = +8\ \mu\text{v-sec}$$

The net area of QRS in lead III will equal

$$(+2) + (-8) = -6\ \mu\text{v-sec}$$

These values are then plotted along the appropriate sides of the triangle in arbitrary units In the present example, 8 units are marked off along the positive half of lead I from the midpoint of that axis. Similarly, 6 units are marked off along the negative portion of lead III. A perpendicular is then dropped from each of these points and their point of intersection noted (*P*) (Fig 4-14A) The line *OP* drawn from the center of the triangle to *P* represents the mean manifest QRS axis, which in this instance makes an angle of −18° with the horizontal.

A planimeter must be used when accurate measurements are essential but in routine determinations the net areas can be estimated adequately by inspection alone. This is rapidly done by multiplying the height of a given deflection (in microvolts) by half its width along the base line (in seconds). The *average magnitude* of $\hat{A}QRS$ in *adults* is 22 μv-sec.

The method of orienting the electrical axis solely in relation to the amplitude of the main deflection in the standard leads is inaccurate. This would only be permissible if these leads were recorded synchronously and the peaks of the deflections to be measured were actually reached at the same instant

The mean P and T axes can be determined in the same manner. The unipolar limb leads can also be used for the derivation of any desired axis

Einthoven's triangle may be converted into a system of coordinates by transposing the three lead axes in such a way that they intersect at their midpoints (Fig 4-14B). The polarities of the leads remain unchanged and their angular relationship is not disturbed. This is known as *Bayley's triaxial reference system* and is more convenient for the

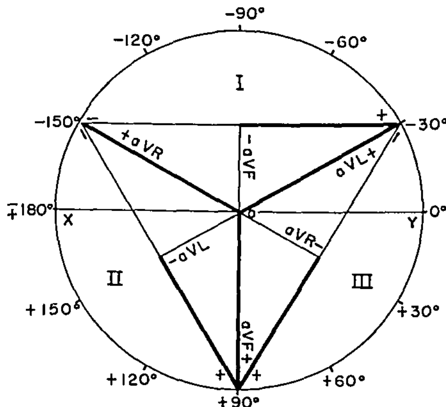


Fig. 4-13. Einthoven's triangle. The position of any frontal plane vector is conventionally expressed in terms of the angle, α, which it makes with the horizontal, *XY*. (See text.)

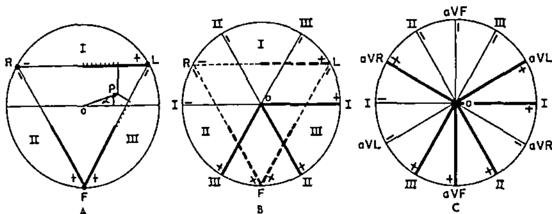


Fig. 4-14. A. Determination of the mean manifest electrical axis (represented by the vector OP). $\alpha = -18°$. (See text) B. Bayley's triaxial reference system. C. Hexaxial reference system. Note that each of the standard lead axes lies between its two component unipolar lead lines. For example, the positive half of lead I lies between the positive portion of aVL and the negative portion of aVR. This enables one to deduce that a given deflection in lead I will be positive when aVR is negative with regard to aVL, etc (See text.)

purpose of plotting the mean manifest vectors than the triangle from which it is derived If the three unipolar limb lead axes are now superimposed on the triaxial system, a *hexaxial reference system* is obtained (Fig 4-14C); in this each axis makes an angle of 30° with its neighbor The diagram shows that aVF is perpendicular to lead I, aVL perpendicular to lead II, and aVR perpendicular to lead III.

Axis Deviation (Fig. 4-15). In adults, the mean manifest QRS axis normally lies in the quadrant between 0 and +90°. If it is between +30 and +90°, there is no deviation

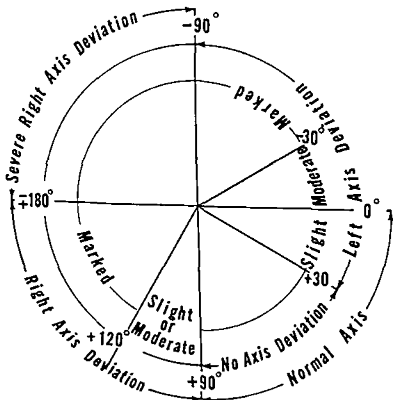


Fig. 4-15. Scheme for the classification of axis deviation. (See text)

of the axis, but between +30 and 0° a slight degree of left axis deviation is present. *If it occupies a position between 0 and −90°, one speaks of definite left axis deviation.* Positions between 0 and −30° constitute moderate left axis deviation; if the angle is between −30 and −90°, marked left axis deviation is said to be present. *Values between +90 and +180° represent right axis deviation;* it may be slight to moderate (+90 to +120°), or marked (+120 to +180°) Axis positions in the remaining quadrant (−90 to −180°) are indicative of severe degrees of right axis deviation.

The mean manifest QRS axis varies considerably during life. In *infancy* and *early childhood,* there is frequently some degree of right axis deviation, and this is always normally observed in newborn infants. This is not surprising when one remembers that at birth the right ventricle has a relatively greater mass in comparison to that of the left ventricle than is the case in the adult Over the years, the electrical axis gradually rotates toward the left as the left ventricle increases in thickness.

Habitus or body build also influences the position of the electrical axis. In the average individual ÂQRS has a value in the neighborhood of +60° In the asthenic type of person with a long thin chest and a vertically placed heart it may be near +90° Obese subjects frequently show an axis position varying from +30 to −30° Similar changes may be observed in the later stages of *pregnancy* and in other conditions associated with elevation of the diaphragm Tracings of such individuals may show a deep Q_3 as well as an inverted P_3 and T_3. These changes indicate that the heart is *horizontal* and has undergone clockwise rotation around its longitudinal axis Thus, slight to moderate left-axis deviation may occur in otherwise healthy adults and is simply an indication that the heart is in the horizontal or semihorizontal position, i.e , that it has rotated in a counterclockwise direction around its anteroposterior axis.

Conversely, it is rare to find definite right axis deviation in a normal adult, even in those of asthenic habitus, and a search should be made in such cases for any underlying disease The possible causes are chronic pulmonary disease, long-standing mitral stenosis or certain types of congenital heart disease, all of which give rise to right ventricular hypertrophy. Left axis deviation to a marked degree is likewise usually associated with those pathological states which lead to left ventricular hypertrophy. It must be added that left ventricular hypertrophy may occur in the absence of any axis deviation and may on rare occasions even be associated with right axis deviation. One explanation advanced for such a situation is the coexistence of right and left ventricular hypertrophy in younger people with combined rheumatic mitral stenosis and aortic valve disease

The Electrical Axis in Various Positions. AXIS AT +60° (Fig. 4-16A). This position is seen in the average normal individual and is represented by the vector OP_2 in the figure. By dropping perpendiculars from the free end of the vector to the axes of the various limb leads, one can make the following observations. the projections lie on the positive limbs of the standard lead lines and the resultant deflections therefore will be upright in leads I, II, and III. The axis is parallel to lead II and the tallest deflection is recorded in that lead. Projection of the mean axis on lead aVF produces resultant positivity while resultant negativity is registered in aVR. Since the electrical axis lies at right angles to aVL, no projection on that lead is possible, which means that the net voltage is zero and the representative complex equiphasic, i.e., the area enclosed by its positive deflection is equal to that enclosed by its negative deflection

AXIS AT +30° (Fig 4-16B). This position is also in the normal range and is represented by the vector OP_R whose components along the different lead axes are indicated by the lines OP_1, OP_2, OP_L and OP_F respectively. The projections lie on the positive portions of leads I and II; this indicates that the main deflections in these leads are upright. The mean vector is perpendicular to lead III which therefore shows equiphasic QRS complexes the net area of which is zero. Leads aVF and aVL record resultant positivity while the main deflection in aVR is downward since the vector lies parallel to the axis of this lead and points towards its negative end.

AXIS AT +90° (Fig 4-16C). Such a position may at times be encountered in normal adults of asthenic habitus and is represented by the vector OP_F The electrical axis in this case is parallel to the positive limb of aVF which therefore shows a tall R wave As it is also perpendicular to lead I, an equiphasic complex (RS) is recorded in that lead. In leads II and

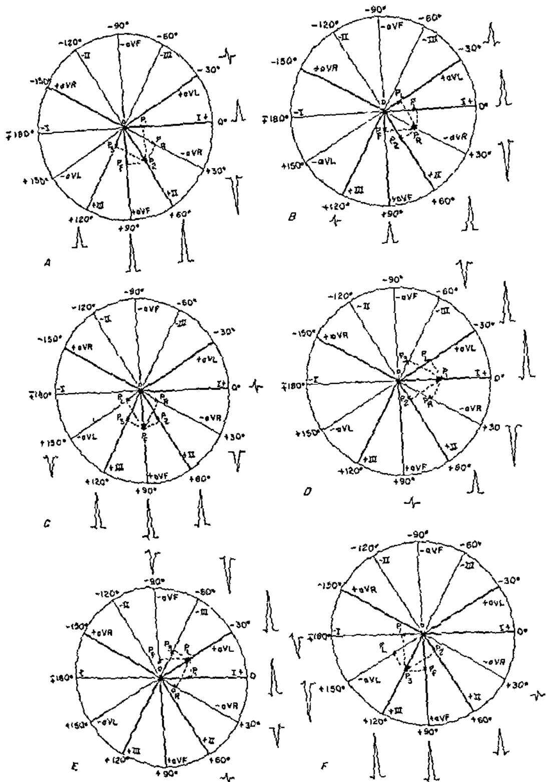


Fig. 4-16. A. ÂQRS at +60°. *To illustrate the derivation of the QRS complexes in the routine extremity leads from a mean manifest electrical axis of known position and magnitude. Only the resultant (net) deflections, as represented by the lengths of the respective projections, can be determined by this method. The minor deflections (q, r, or s) have been added merely on the basis of the probability of their appearance in actual tracings with a mean axis in the corresponding position.* B. ÂQRS at +30°. C. ÂQRS at +90°. D. ÂQRS at 0°. E. ÂQRS at −30°. F. ÂQRS at +120°. (See text.)

III, the net areas of QRS are positive and equal so that tall R waves are inscribed. In aVR and aVL, the resultant negativity is accounted for by the fact that the projection of the vector is to the negative side in each instance

AXIS AT 0° (Fig. 4-16D). This position represents a slight degree of left axis deviation and may be seen in sthenic or obese individuals with normal hearts The projection of OP_1 on lead II is to the positive side, that on lead III to the negative side. Since the axis is parallel to the positive limb of lead I, the tallest upward deflection is recorded in this lead. The amplitude of the R_1 wave is thus greater than that of R_2. The main deflection is upright in leads I and II but downward in III. The R_3 wave, if present, is smaller than R_2. The negative excursion in lead III may be a Q or an S wave, and the configuration of the complex therefore either Qr or rS Resultant positivity is recorded in aVL. The net area of QRS is zero in aVF and negative in aVR

AXIS AT −30° (Fig. 4-16E). This is an example of moderate left axis deviation. The mean vector is parallel to the positive limb of aVL which therefore shows a tall R wave As it is also perpendicular to the axis of lead II, it cannot be projected onto that lead. The net area of the QRS complex in II is therefore zero, which is reflected by the equiphasic (RS) complex In lead I, the main deflection is upright while in lead III it is downward. Resultant negativity is registered in both aVR and aVF It should be noted that the projections OP_1 and OP_3 are of equal length Since they represent the net areas of QRS in leads I and III respectively, it follows that these areas are equal Since they are of opposite polarity, their algebraic sum must be zero As in this instance the net area of QRS in lead II is also zero, then I + III = II as stated by *Einthoven's law*. However, the validity of this relationship can be demonstrated for any given position of the electrical axis, whether instantaneous or mean. Further deviation of the axis to the left produces negativity in lead II which then resembles lead III rather than lead I.

AXIS AT +120° (Fig 4-16F) This is an example of moderate right axis deviation. Projection of the vector OP_3 onto the axes of leads I and II reveals that the main deflection will be downward in the former and upright in the latter. The mean axis is parallel to the positive portion of lead III which therefore exhibits the tallest upward deflection. The R_3 wave is thus of greater amplitude than R_2, while R_1 is relatively small. The usual QRS configuration in lead I is rS. The aVF lead shows resultant positivity. The net area is negative in aVL and zero in aVR. With more marked deviation of the axis to the right, lead II will show resultant negativity and resemble lead I rather than lead III.

The foregoing examples illustrate the following general principles:

1. When the electrical axis lies parallel to a particular lead, its projection is maximal in that lead which shows the largest net area and amplitude. Whether this area and hence the main deflection has a positive or a negative value depends on the direction in which the vector points. For instance, a vector parallel to lead I and pointing along the 0° axis (towards the patient's left) will record resultant positivity. On the other hand, a vector parallel to the 180° axis (pointing to the patient's right) will produce resultant negativity in lead I. As the angle between the vector and the lead axis increases, the projection of the former will decrease progressively.

2 When the electrical axis is perpendicular to a given lead its projection on that lead will be zero, and so will be the net area of the complex. Such a complex will be equiphasic and is frequently of small amplitude. It is immaterial in these circumstances whether the vector points towards the lead axis or away from it. No projection will be possible in either case. By the same token, electromotive forces acting at right angles to the plane of Einthoven's triangle cannot be recorded in any of the standard or unipolar extremity leads as they have no components in that plane Such purely anteroposterior (or posteroanterior) forces can, however, be recorded in the unipolar precordial leads whose axes extend from the respective electrode position on the chest wall to the electrical center of the heart. The reason for this is the same as that given in the discussion of the axes of the unipolar limb leads.

3 The hexaxial reference system enables one to perform a rapid estimation of the approximate direction of the mean vector in the frontal plane. For instance, if lead aVF shows a net area of zero, the electrical axis must be at right angles to that lead, and hence parallel to lead I. The orientation of the vector in space is of greater importance and can be ascertained by *Grant's method* (Chap 7). This involves the determination of the precordial lead which shows a transitional complex and application of the knowledge that the mean vector

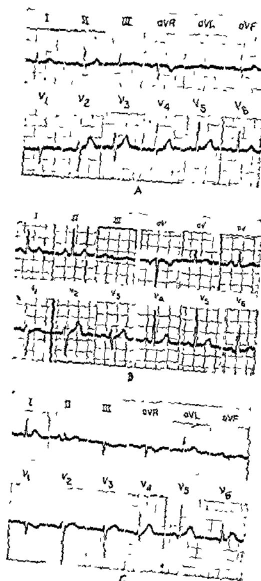


Fig 4-17. A Normal electrocardiogram The QRS complex in aVL is equiphasic and small. The mean frontal plane axis therefore lies at +60° (parallel to the positive limb of lead II). In the precordial leads, V_3 shows an equiphasic complex and therefore lies in the transition zone. The mean QRS vector must be perpendicular to the lead line of V_3; the electrical axis thus points posteriorly, inferiorly, and to the left, making an angle of approximately 15° with the frontal plane, as well as maintaining its 60° angle with the horizontal. B The QRS complex in III is very small, with a net area close to zero. The mean frontal plane vector thus lies at +30°, i.e., along the negative limb of aVR, pointing inferiorly and to the left. The precordial transition zone for QRS is located between V_3 and V_4 (but much closer to V_3 than to V_4). This again indicates a slight posterior rotation (approximately 20°) of the mean spatial vector (From Lipman and Massie, Clinical Unipolar Electrocardiography, 1956). C. Normal electrocardiogram showing left axis deviation. Lead aVF shows minimal resultant negativity. This places the mean frontal plane QRS vector slightly above the zero degree axis (at approximately −10°). The positive deflection in lead II indicates that it is not close to −30°. The transition zone in the chest leads lies between V_3 and V_4, indicating that the spatial axis is directed posteriorly, making an angle of approximately 25° with the frontal plane.

for the horizontal plane must lie at right angles to the axis of that lead. The vector in the frontal plane is then tilted anteriorly or posteriorly until it lies perpendicular to the axis of the chest lead showing the transition complex. This method is only a rough approximation but is nonetheless useful in the vectorial analysis of electrocardiograms (Fig 4-17).

The normal QRS axis is directed inferiorly, to the left, and posteriorly to a varying degree In the presence of left axis deviation, this posterior displacement usually becomes more marked In right axis deviation the rotation ... either anterior or posterior.

... ous extremity leads as outlined above and illustrated in Fig 4-16 reveals that, when ÂQRS lies within the normal range (0 to +90°), lead aVR invariably shows a resultant negative deflection, and this also holds true for slight deviations of the mean axis to the right or left. In other words, the lead axis of aVR always lies in the negative half of the electrical field for those positions of ÂQRS which are encountered in the great majority of healthy adults. The configuration of aVR is therefore not influenced to any extent by changes in heart position. All the components of this lead generally show fairly high voltage. The actual configuration of the QRS group may be rS, QS, or Qr.

By contrast, the appearances of aVL and aVF are affected to a considerable degree by changes in the position of the axis. When there is no axis deviation (i.e., between +30 and +90°), the QRS complexes in aVL may be small and transitional, upright or inverted In this range the amplitude of the main deflection is only moderate but increases when the heart rotates into a horizontal position (near 0°)

In that case a qR or Rs complex is recorded, whereas rS or QS configurations are associated with a vertical heart. In lead aVF, the main QRS deflection is upright for axis positions between +30 and +90°. When the heart is vertical (near +90°), the usual configuration is qR, the R wave being tall, while transitional or rS complexes are seen with horizontal positions of ÂQRS, depending on the degree of deviation of the axis to the left. When the heart is in an intermediate position, both aVL and aVF show upward QRS deflections of similar configuration and amplitude

It is apparent that the method of derivation of the QRS complex from the mean axis merely indicates the resultant deflection in each of the six limb leads and cannot give any information concerning the presence or absence of the minor deflections and their amplitudes. Such details can only be obtained if multiple successive instantaneous vectors are drawn and projected onto the various lead axes

Any QRS complexes which are of low voltage are commonly thickened or slurred. Such changes may also be observed on the upstroke or downstroke of taller deflections and may be disregarded if they occur near the base line as an isolated finding *Slurring or notching near the peak of a main deflection is more likely to be abnormal*

Q waves are present in one or more standard leads in approximately 70 per cent of normal tracings. In vertical hearts *they are seen in* leads II and III, in horizontal hearts they occur in lead I The amplitude of the Q wave in a given standard lead is usually expressed as a percentage of the R wave in the same lead or of the tallest deflection in any of the three leads. Statistical studies on normal subjects have shown that, with rare exceptions, the depth of the Q wave in I and II does not exceed 20 per cent of the amplitude of the corresponding R wave or 15 per cent of the main deflection in the other two leads However, if the heart is horizontal, QII may exceed 25 per cent of RII in a small proportion of cases In lead III, deep Q waves may normally be found in association with either right or left axis deviation and clockwise rotation In the latter instance, the Q wave becomes the main deflection.

The Mean Manifest Electrical Axis of P (ÂP). In most normal subjects, the mean manifest electrical axis of atrial activation (ÂP) makes an angle of approximately +60° with the horizontal. The sinus P wave is therefore usually upright in the three standard leads, being most prominent in lead II. It is always inverted in aVR, usually upright in aVF, and may be positive, diphasic, isoelectric, or negative in aVL. However, the normal mean P axis may vary within a fairly wide range and has been found to lie both farther to the left and farther to the right of its usual position. Deviation of ÂP to the left is therefore responsible for the appearance of flat or inverted P waves in lead III; this is not infrequently the case in stocky or obese individuals and in conditions associated with elevation of the diaphragm and merely reflects the fact that the heart occupies a horizontal position.

The Mean Manifest Electrical Axis of T (ÂT). In the frontal plane ÂT normally parallels ÂQRS fairly closely in the various heart positions. This fact implies that ÂT and ÂQRS rotate together and serves to explain the observation that the T wave generally points in the same direction as the main QRS deflection Upright T waves are therefore normally seen in leads I and II, while in III the T wave may be upright, diphasic, or inverted. In a vertical heart with right axis deviation the T wave is generally upright but may be of low amplitude in lead I and is tall in lead III. In a horizontally placed heart with left axis deviation, the T wave is upright and of high amplitude in lead I, *but frequently inverted in* lead III, especially when there has been associated clockwise rotation around the longitudinal axis. In aVR the T wave is normally inverted. In aVL its configuration is variable. When the main QRS deflection is downward the T wave may be either flat or inverted, when QRS shows marked resultant positivity (qR) the T wave is likewise upright as a rule. In aVF the T wave usually parallels the main QRS deflection, but may point in either direction if the voltage of the QRS complex is low

THE VENTRICULAR GRADIENT

In an experimental muscle strip immersed in a conducting medium, both depolarization and repolarization proceed in the same direction, since their representative dipoles are opposite in sense, the resulting deflections are of opposite polarity. If the external environment is uniform and one imagines the strip to be divided into a number of equal segments, the

time necessary for activation is the same for each. Each portion of the muscle therefore *remains in* the excited state for the same length *of time*, and the segments are repolarized in *the same order in* which they were depolarized. The duration of the recovery process, and hence that of electrical systole, is the same for each segment. In other words, there are no local variations in the duration of the excited state and, under such circumstances, no gradient exists (Fig. 4-18A). If one measures the areas enclosed by the two deflections, they are found to be equal. Since they are of opposite polarity, their algebraic sum will be zero. Therefore,

$$\hat{A}QRS + (-\hat{A}T) = 0$$

If one end of the strip is cooled, the onset of the recovery process will be maximally delayed in that zone, and the duration of systole correspondingly prolonged. This effect of local cooling will also make itself felt in the adjacent segments but will *diminish progressively with* increase in distance from the cooled portion (Fig. 4-18B). *The result is that repolarization will proceed in a direction opposite to that of depolarization, which remains unchanged.* From this one sees that it is the modification of the recovery phase which alone is responsible for the prolongation of systole. In this instance, there are local variations in the duration of the excited state. The line is now no longer horizontal but oblique, and forms the

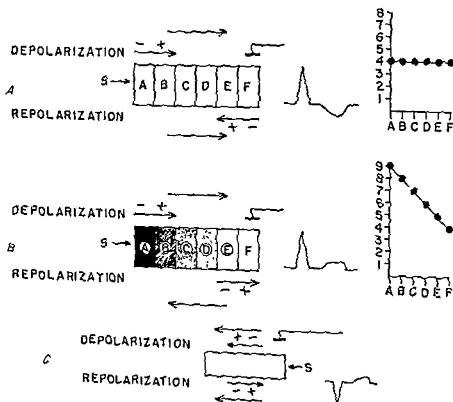


Fig. 4-18. A. The muscle strip is stimulated at segment A. The exploring electrode is applied at F. The large arrows indicate the direction of depolarization and repolarization respectively. The smaller arrows represent the dipoles of these two processes. When the duration of electrical systole is plotted against the individual muscle segments a horizontal line is obtained, which indicates that no gradient exists. (After Cabrera.) B. The muscle strip has been cooled at A. The course of depolarization is unaffected whereas that of repolarization is reversed because the onset of recovery is delayed in decreasing order from A to E. A sloping line results when systolic duration is plotted against segments A to F. A (temperature) gradient is therefore present. The T-wave change is primary. (After Cabrera.) C. The muscle strip receives a stimulus S at the site of the exploring electrode. The large arrows indicate the direction of depolarization and repolarization, respectively. The smaller arrows represent the dipoles of these two processes. The alteration in the course of depolarization has caused a change in the order of repolarization. The T-wave change is secondary.

graphic representation of the existence of a gradient, in this case a *temperature gradient* (Fig. 4-18B). *Both deflections are now upright, and the algebraic sum of their areas is no longer zero.* Furthermore, the magnitude of $\hat{A}T$ depends on the characteristics of the agent responsible for the delay in recovery. In effect, the sum of the mean vector representing depolarization and that representing repolarization equals a *third vector quantity*, namely, *the gradient* ($\hat{G}$). Thus,

$$\hat{A}QRS + \hat{A}T = \hat{G}$$

As the sum or resultant of any two vectors is obtained by construction of the parallelogram of forces, the direction and magnitude of $\hat{G}$ can easily be found by a determination of the mean manifest axes of QRS and T as described in a preceding section $\hat{A}QRS$ and $\hat{A}T$ form the two sides of the parallelogram. If the figure is completed, $\hat{G}$ is represented by the diagonal.

Proof of this point can be furnished, and the concept under discussion clarified, if the problem is approached from a different angle. In the first example the area of the QRS complex was noted to be equal but opposite in sign to the area of the T wave. The mean manifest axis of the QRS complex can be represented by a vector of given magnitude and sense. The mean manifest axis of the T wave can similarly be drawn as a vector of the same magnitude but of opposite sense.

If this arrangement obtained in the normal adult heart, the ECG would show QRS and T complexes pointing in opposite directions in all the leads. However, it is known from experience that the T waves are actually upright in most leads, or at any rate parallel the main QRS deflections fairly closely The conclusion is that there must be another force at work which tends to rotate the T vector from its anticipated position into its actual position, causing it to lie more or less parallel to the mean QRS axis *This force is the ventricular gradient* ($\hat{G}$) *which is always normally present in the intact heart.* The mean manifest T axis ($\hat{A}T$) can therefore be regarded as the resultant of two vectors, namely, the theoretical T axis and the ventricular gradient The first of these quantities, ($\hat{A}T$), can be plotted from two of the limb leads as outlined previously. The theoretical T axis can also be found since it is known to equal $\hat{A}QRS$ in magnitude but be opposite in sense to the latter. As $\hat{A}T$ is the diagonal of a parallelogram of forces, one side of which is formed by the anticipated T vector, the magnitude and direction of the unknown component $\hat{G}$ can be found by simply completing the figure.

If the parallelogram having the sides $\hat{A}QRS$ and $\hat{A}T$ is now constructed it will be seen that its diagonal is in fact formed by $\hat{G}$. In other words, the ventricular gradient is the vectorial sum or resultant of the mean QRS and T axes and points from the area in which the duration of the excited state, and hence that of electrical systole, is longest to that where it is shortest. It is therefore also defined as a measure of the local variations in the duration of the excited state.

The fact that the mean QRS and T vectors normally have much the same sense, makes it clear that the processes of depolarization and repolarization travel in opposite directions, the former from endocardium to epicardium, the latter from epicardium to endocardium. This phenomenon has been explained on the basis that the subendocardial muscle is exposed to the high intraventricular systolic pressure, with consequent retardation of the onset of repolarization in that region. The ventricular gradient is therefore a normal physiological entity but, under certain circumstances, it may also indicate the presence of an underlying pathological process.

$$\hat{A}QRS + \hat{A}T = \hat{G}$$

therefore $\hat{A}T = \hat{G} - \hat{A}QRS$

This means that the amplitude, duration, and polarity of a T wave depend on two factors: the magnitude and direction of the QRS complex and the ventricular gradient. A change in either of these will result in alterations of the T wave

If there is an alteration in the ventricular gradient without any accompanying modification of the depolarization process the resulting *T wave change* is spoken of as *primary*. The regional cooling of the muscle strip referred to above is an example of this, since depolarization remained unaffected while the changes in the recovery phase could be ascribed to the creation of the gradient.

This experiment can be duplicated clinically by giving a normal individual a large volume

of iced water to drink. This maneuver chills the posterior aspect of the ventricular epicardium and may produce temporary T-wave alterations without affecting the QRS complexes. Frequently, however, primary T-wave changes are indicative of absolute or relative myocardial ischemia secondary to coronary artery disease, left ventricular hypertrophy, or both. Administration of digitalis also is followed by primary T-wave changes.

A *secondary T-wave change* (Fig 4-18C) involves an alteration in the order of repolarization which occurs as a direct result of an alteration in the course of depolarization Bundle branch block is the best example of this type, but ventricular extrasystoles and the Wolff-Parkinson-White (pre-excitation) syndrome also belong to this category. The T waves are inverted in leads where the net QRS area is positive, and vice versa. $\hat{A}$QRS and $\hat{A}$T tend to rotate away from each other to the same degree while the ventricular gradient remains in a normal position. For this reason, secondary T-wave changes do not in themselves reflect the presence of myocardial pathological changes, except by inference.

Primary T-wave changes may, of course, be superimposed on secondary ones This is particularly likely to happen in bundle branch block where mere inspection of the tracing may not reveal whether the inverted T waves are secondary to altered depolarization or whether there is also an ischemic component. At the present time, this is probably the only instance in which determination of the ventricular gradient may be of diagnostic value. If the positions of $\hat{A}$QRS and $\hat{A}$T are determined, that of $\hat{G}$ can likewise be deduced A ventricular gradient lying within the accepted normal range would suggest bundle branch block only, whereas a definitely abnormal position of $\hat{G}$ would favor a diagnosis of block with superimposed ischemia.

Normal Values of $\hat{G}$. The ventricular gradient is customarily represented by its projection onto the frontal plane, and the values given below therefore refer to Einthoven's triangle According to studies by Ashman and Byer the average magnitude of $\hat{G}$ was found to be 13 (Ashman) units, with a maximum of 23 units The position of $\hat{G}$ ranged between −17 and +56° in a large series of normal subjects but was found to vary considerably with the degree and direction of rotation of the heart around its *longitudinal* axis. In normal individuals, $\hat{G}$ should not deviate more than 30° to either side of $\hat{A}$QRS. Bayley et al. found $\hat{G}$ to be not more than 24° to the right or more than 35° to the left of $\hat{A}$QRS. Special methods and equipment for the determination of the spatial orientation and magnitude of the ventricular gradient and its components have been described.

THE EFFECT OF DRUGS ON THE ELECTROCARDIOGRAM

Digitalis. Therapeutic doses of digitalis produce certain changes in the configuration of the ventricular complex, but their recognition in a given tracing is not easy, and may actually be impossible. As a rule, *digitalis affects repolarization without disturbing depolarization* The changes thus appear in the S-T segment and T wave and are of the "primary" type (Fig. 4-19). There is *abbreviation of electrical systole* in the subendocardial region of the ventricles due to a decrease in the normal delay in the onset of repolarization. The recovery process is therefore accelerated and, at least in part, proceeds in a direction from endocardium to epicardium. This manifests itself in the electrocardiogram by *an abbreviation of the Q-T interval and a displacement of the S-T segment in a direction opposite to that of the main QRS deflection* resulting from the appearance of early repolarization forces. The S-T segment is therefore depressed in leads in which the QRS complex shows resultant positivity, and vice versa The segment is characteristically "sagging" or "scooped," and this upward concavity is often the earliest change, before deviation of RS-T is superimposed Sometimes the displaced segment appears as a straight line. Since the subepicardial region is not affected by this drug to any significant extent, some repolarization may take place in the normal manner from epicardium to endocardium, and this will be reflected in the tracing by a small terminally upright T wave following the depressed S-T segment. However, as the effects of the drug become progressively more pronounced, the T wave will show complete inversion, its nadir lying close to its termination

The difficulty in the interpretation of these changes lies in the fact that they may also be

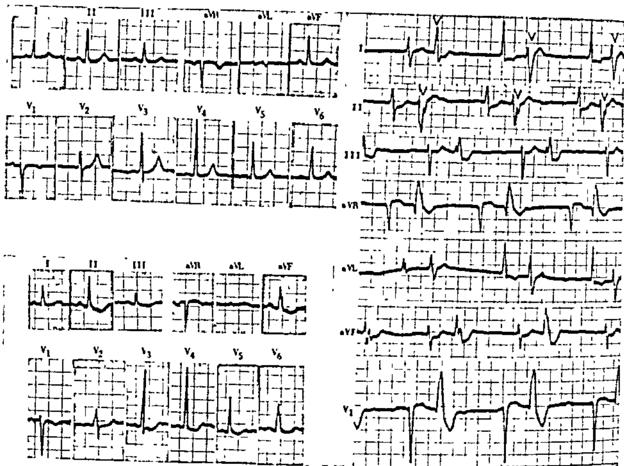


Fig. 4-19. Digitalis effect. Upper left. Tracing prior to the administration of digitalis. Lower left. Tracing of the same patient after digitalization. Note the characteristic "sagging" of the S-T segments and flattening of the T waves Right Digitalis intoxication (in another patient) resulting from excessive dosage. Each normal beat is followed by a ventricular premature contraction (bigeminal rhythm). In leads I and aVF the premature beats arise from different foci. Note also the S-T–segment changes due to digitalis effect and the presence of atrial fibrillation. (*From Lipman and Massie, Clinical Unipolar Electrocardiography, 1956.*)

seen in patients with ventricular hypertrophy and ischemia Administration of digitalis to such patients tends to accentuate the preexisting changes It is sometimes stated that ischemia produces upward convexity of the RS-T segment whereas digitalis gives rise to an upward concavity and that this feature serves as a differential criterion. This is not a reliable rule, however, and should not be used It is also worth noting that therapeutic doses of digitalis sometimes produce little or no change in electrocardiograms, so that the tracing is still within normal limits Mere inspection of a tracing can therefore not always reveal with certainty whether or not a patient has been receiving digitalis. Administration of the drug may be suspected from the record, but the coexisting heart disease can duplicate or completely mask its effects. This makes the clinical information all-important, not only for those concerned with the therapeutic problems involved but also for the cardiologist who may be called upon to interpret the tracing without having seen the patient.

Overdigitalization sooner or later leads to *intoxication*, with potentially serious consequences if certain earlier warning signs are not recognized In approximate order of appearance these are·

1 Increasingly frequent *ventricular premature contractions* in cases in which they had not been present previously Bigeminal or trigeminal rhythm may follow (Fig. 4-19).

2 Progressive *interference with atrioventricular conduction* This causes initially a prolongation of the P-R interval while later there may be partial or even complete AV block.

3 Short runs of *ventricular premature contractions*, *multifocal ventricular premature beats*, or both

4 *Ventricular tachycardia,* which may be followed by ventricular fibrillation and death

It must be emphasized that digitalis can be responsible for *virtually* any type of arrhythmia, such as nodal tachycardia, atrial fibrillation, *AV dissociation, and, more rarely, atrial*

It should be kept in mind that the arrhythmias may be precipitated by loss of potassium from *the body*. Either prolonged diarrhea which may follow the administration of oral antibiotics, or diuresis caused by *mercurial compounds* is a possible cause of this condition.

Quinidine. Therapeutic doses of this drug produce a uniform increase in the duration of the excited state, which means that the refractory period is prolonged. The onset of *repolarization is delayed and the rate of* its propagation uniformly *retarded* so that no change in the direction of this process occurs. The electrocardiogram therefore shows *lengthening of the S-T segment and widening and flattening of the T wave. The over-all result is a prolongation of the Q-T interval* Larger amounts of *quinidine* may give rise to generalized conduction delay, *an expression of its depressant effect Prolongation of the QRS interval* should therefore be looked for in all cases receiving the drug A QRS complex spread exceeding 25 per cent of its original duration is *regarded as an indication* for discontinuing the drug. Other *effects* are slowing of the rate, widening of the P wave, and *prolongation* of AV conduction

Occasionally, quinidine may have the opposite and undesirable effect of increasing the ventricular rate due to a blocking action *on* the vagus. *Toxic doses* may lead to ventricular fibrillation or cardiac *standstill* resulting from suppression of the cardiac pacemaker.

Pronestyl (Procaine Amide). The effects *of* this agent on the *electrocardiogram are similar* to those of quinidine. There may be flattening or inversion of the T waves and prolongation of the Q-T interval *as well as* some delay in AV conduction Moreover, electrical alternans and reduction *in the* amplitude of the QRS complexes have also been observed Progressive widening of QRS reflects the toxic effect of the drug and is an indication that its administration should cease. By depressing the supraventricular *pacemakers* and delaying AV conduction, Pronestyl may therefore precipitate

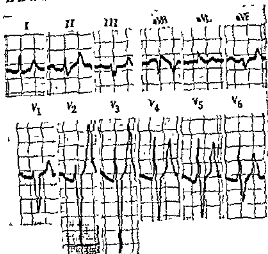


Fig. 4-20 Case of chronic glomerulonephritis in renal failure with hyperkalemia (serum potassium level 7.6 mEq per liter). Note the tall, peaked T waves, particularly in leads II and V_2 through V_6 The QRS interval is slightly prolonged (0.11 sec) (From Lipman and Massie. Clinical Unipolar Electrocardiography, 1956.)

ventricular arrhythmias or cardiac standstill, *particularly* in patients with advanced myocardial damage.

Emetine. Therapeutic doses of this drug produce flattening or *pointed* inversion of the T waves, as well as prolongation of the *Q-T* interval, in a high proportion of cases. *Areas* of myocardial necrosis have been demonstrated in at least one instance The P-R interval may *also* be prolonged *These* changes *usually* dis-

of this drug has a paralytic effect on the vagal nerve endings, with resultant tachycardia, tall P waves, shortening of the P-R interval, and lowering of the T waves, also occur. Prolonga*tion of P-R interval* due to increased vagal tone or rheumatic carditis can be abolished by intravenous doses of atropine

THE EFFECT OF ELECTROLYTE IMBALANCE

Since heart disease frequently coexists with renal diseases, *metabolic* disease, or both, and *since* the *electrolyte disturbances* associated with them may be reflected *in* certain changes in the electrical activity of the *myocardium*, it is important to know the *changes produced by*

electrolyte imbalance. The ions principally concerned are *calcium* and *potassium*.

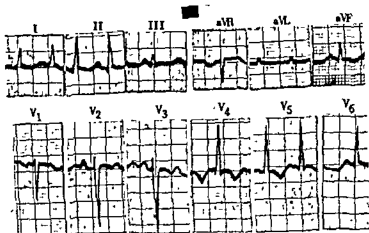
Hypercalcemia. High serum-calcium levels produce *a shortening of the Q-T interval* which, however, may only become apparent by comparison of serial tracings. The ascending limb of the T wave has its origin at the S-T junction so that the S-T segment as such is no longer recognizable. There may also be some increase in the amplitude of the T waves.

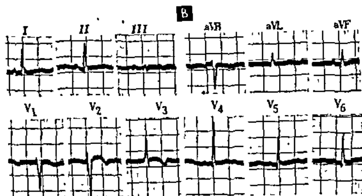
Hypocalcemia. Low serum-calcium levels produce *a prolongation of the Q-T interval* which is entirely due to lengthening of the S-T segment. No T-wave changes are seen unless there is a concomitant disturbance of other electrolytes or coexistent myocardial disease. There is some evidence to suggest that an inverse relationship exists between the level of the ionized fraction of the serum calcium and the Q-T interval.

Hyperkalemia (Hyperpotassemia). No abnormalities are apparent until the serum potassium has risen to a level of approximately 7 milliequivalents per liter (mEq/liter) or more, which is well above the upper limit of normal values If, however, the increase in potassium has been accompanied by a fall in the serum-sodium level, as may occur in cases of metabolic acidosis, the characteristic changes may manifest themselves with a smaller rise in serum potassium. The earliest change is the appearance of tall, peaked, and symmetrical T waves the width of which decreases with increase in their amplitude This is best seen in leads I or II and V_2 through V_6 (Fig 4-20). Further rises in the potassium level produce a progressive depression of the SA node which initially leads to periods of *sinus arrest* with nodal or ventricular escapes but eventually results in atrial standstill and disappearance of the P waves. The QRS complex begins to spread at serum levels of about 10 mEq/liter, obliterating the S-T segment, and finally merging with the T wave. The end result is a tall, bizarre, diphasic deflection Cardiac standstill and death supervene at levels ranging from 12 to 14 mEq/liter.

Hypokalemia (Hypopotassemia). The electrocardiographic appearances associated with a low serum-potassium level are somewhat similar to those following therapeutic doses of digitalis, the chief difference being that *the Q-T interval is prolonged.* Leads I (or II), V_5 and V_6 usually show these changes most clearly (Fig. 4-21). Increased Q-T duration, together with broadening and flattening or even complete inversion of the T wave, is noted in the earlier stages. If the serum concentration falls to about 1.5 mEq/liter, S-T segment depression appears, and prolongation of the P-R interval may be seen at times. Bellet has described five distinct "patterns" in hypokalemia, one of which mimics the changes associated with subendocardial injury while another duplicates those of pericarditis. In some tracings, the appearance of tall U waves partly fused with the T waves makes the determination of the Q-T interval impossible, and Q-U has to be measured instead. This has led some investigators to contend that the prolongation of the Q-T interval in hypopotassemia is only apparent, being due to the inclusion of the U wave in the calculation. Where the T and U waves are separate and distinct, the duration of the Q-T segment is found to be normal, but the Q-U interval is prolonged. The parallelism between serum concentrations of potassium and electrocardiographic appearances is by no means close at all levels. It has been suggested that the correlation is good at both high (above 6.7 mEq/liter) and low (less than 2.3 mEq/liter) levels, while in the intermediate range the electrocardiogram frequently fails to parallel the biochemical derangement as determined by laboratory methods. An electrocardiographic diagnosis of hypokalemia may therefore be difficult (if not impossible) if coronary insufficiency is present or if the patient has been receiving digitalis. Furthermore, prolonged hypokalemia has been shown to give rise to areas of irreversible focal necrosis in the myocardium with corresponding changes in the tracing. Attention has already been drawn to the fact that potassium depletion tends to potentiate the toxic effects of digitalis. These may be promptly abolished by the oral or intravenous administration of potassium chloride.

Hypokalemia and hypocalcemia may occur together in a number of conditions, such as *sprue, uremia,* or *hepatic coma.* The tracing shows the prolonged Q-T interval of hypocalcemia as well as the low T waves due to hypopotassemia The double diagnosis is usually difficult to make on the basis of the tracing, and the changes may be ascribed to the effects





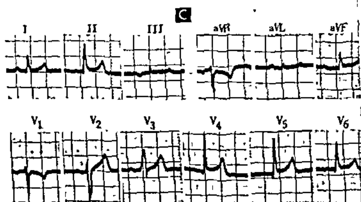


Fig. 4-21. Hypokalemia occurring in a 17-year-old girl in diabetic ketosis A. Patient admitted in coma There is widespread flattening and inversion of the T waves The Q-T interval was considered to be prolonged in relation to the rapid rate B. Two days later, after appropriate therapy which included potassium Note the improvement in the T-wave configurations. C. Five days later. Tracing within normal limits. (*From Lipman and Massie. Clinical Unipolar Electrocardiography,* 1956.)

of the hypokalemia alone. Less difficulty is encountered when hypocalcemia is associated with hyperkalemia. If hypercalcemia and hypokalemia are found in the same patient, the Q-T interval may be prolonged and the T waves become flattened, so that the resulting picture will be interpreted as being that of hypokalemia only.

THE EFFECT OF DIETARY FACTORS

Malnutrition. Severe starvation has been shown to produce marked sinus bradycardia, low amplitude of all deflections, intraventricular block and prolongation of the Q-T interval. Resumption of a normal diet causes all these changes to disappear.

Thiamine (Vitamin B_1) Deficiency. The electrocardiogram shows tachycardia and tall P waves. The P-R interval is freqeuntly shortened but may be prolonged. The QRS complex may be of low voltage and its duration slightly prolonged The amplitude of the T wave is frequently low, or it may be actually inverted, in two or all three standard leads, a change which has been shown to be reversible upon the administration of thiamine. The S-T segment shows no depression and may even be elevated in the early stages The Q-T interval is prolonged. High U waves have also been described in this condition.

Nicotinic Acid Deficiency. This gives rise to the clinical picture of *pellagra.* The electrocardiographic findings include low voltage and prolongation of the P-R and Q-T intervals, as well as low amplitude or actual inversion of the T waves in one or all three standard leads. Administration of nicotinic acid leads to a reversal of all these changes.

THE EFFECT OF HORMONES ON THE ELECTROCARDIOGRAM

Insulin. The administration of insulin in doses large enough to produce hypoglycemia has been and still is the therapeutic aim in certain psychiatric conditions Hypoglycemic shock causes sinus tachycardia, tall P waves, particularly in leads II and III, and usually a shortening of the P-R interval There is also a widening of the QRS complex which has been ascribed to the hypoglycemia itself The T wave decreases in amplitude in normal adults, especially in leads I and II, and the S-T segment is depressed, chiefly in leads II and III. In patients with coexistent coronary artery disease, hypoglycemia can precipitate precordial pain accompanied by depression of S-T segments and inversion of T waves. The T-wave changes have been shown to vary directly with the blood sugar level and are abolished by the injection of glucose. Cases of spontaneous hypoglycemia show similar changes. Prolongation of the Q-T interval has also been reported, and is thought to be due to a specific effect of insulin. A high proportion of adult diabetics show abnormal tracings, either at rest or after exercise, the underlying cause being the associated coronary artery disease.

Ovarian Insufficiency. Depression of the S-T segment and low T waves have been observed in certain cases of ovarian insufficiency and during the menopause. These changes can be abolished by the administration of estrogens.

Epinephrine. An injection of epinephrine produces tachycardia, with a corresponding increase in the amplitude of the P waves, as well as shortening of the P-R and QRS intervals. Slight depression of the S-T segment and flattening of the T waves has been reported in normal individuals while subjects with coronary artery disease show pronounced depression of the S-T segment and T-wave inversion. In the latter group, previously inverted T waves were seen to become upright following the administration of epinephrine Although epinephrine dilates the coronary arteries, it also increases the work of the heart, the net effect being a relative myocardial hypoxia of a varying degree. For this reason, administration of epinephrine has been used as a means of diagnosing coronary artery disease but, in view of the risks involved, the method has been abandoned in favor of exercise tolerance tests.

Isuprel (Isopropylarterenol). The effects of this drug are similar to those of epinephrine with the exception that the degree of depression of the S-T segment and T-wave inversion is more marked than with the latter. These changes are accentuated by nitroglycerin which increases the typical blood pressure drop due to Isuprel. On the contrary, nitroglycerin prevents inversion of the T waves when administered simultaneously with epinephrine. Isuprel has an excitatory effect on cardiac pacemakers at or above the AV node and abolishes ventricular standstill resulting from complete AV block In contrast to epinephrine, this drug

does not predispose to or perpetuate ventricular tachycardia and fibrillation. In cases showing AV-conduction disturbances, these arrhythmias can in fact be abolished by the use of Isuprel.

Norepinephrine. This agent produces bradycardia and lowers the amplitude of the P waves in normal individuals while the T waves become taller. Nodal rhythm has also been observed. Tracings of patients with paroxysmal hypertension due to a *pheochromocytoma* may show atrial fibrillation or AV dissociation, as well as deformed ventricular complexes during a crisis. The T waves may remain inverted for several weeks following each paroxysm but become upright when the tumor is removed. The latter changes are probably ischemic in origin.

Thyroxin. THYROTOXICOSIS In this condition, the electrocardiogram shows sinus tachycardia and *tall P waves* in leads II, III, and aVF. These effects can be duplicated by the administration of thyroxin to normal subjects. The P-R interval may be shortened, normal, or prolonged, depending upon the severity of the disease. The increased amounts of circulating thyroid hormone which are found in advanced cases of thyrotoxicosis have been held responsible for the development of AV block. Atrial fibrillation may supervene and is heralded by widening and notching of the P

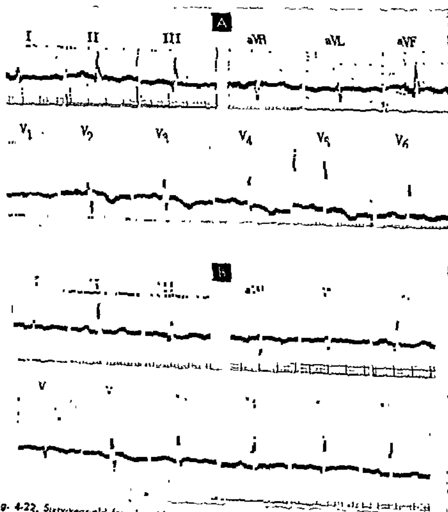


Fig. 4-22. Sixty-year-old female with myxedema. A. Before thyroid therapy. Note the flat or inverted T waves in I, II, III, aVF, and V_3 to V_6. B. Two weeks later, on thyroid therapy. Note the general improvement in the configuration of the T waves. (From Lipman and Massie. Clinical Unipolar Electrocardiography, 1956.)

waves. High voltage of the QRS complex is a common finding, and intraventricular conduction disturbances are known to occur. The heart tends to assume a vertical position in the majority of cases, causing the electrical axis to rotate to the right. T-wave changes vary from an increase in amplitude in mild cases to frank inversion and depression of the S-T segment in those of greater severity. Thyroidectomy and therapy with antithyroid drugs restore the normal configurations.

MYXEDEMA. Here the tracing shows characteristically *low voltage* of all deflections This may be due to the short-circuiting effect of the myxedematous tissues or to the presence of a pericardial effusion. Administration of thyroid extract will reverse these changes The presence of pointed inverted T waves is suggestive evidence of coexistent coronary artery disease (Fig. 4-22).

THE EFFECTS OF PHYSICAL AGENTS

Temperature. If several healthy individuals are given 800 to 1,000 ml of iced water to drink, the chilling effect on the epicardial surface of the posterior wall of the left ventricle manifests itself in a reversal of the direction of the T wave in a majority of cases. As has been explained previously, the cooling of a particular region of muscle prolongs the duration of the excited state, with a concomitant change in the direction of repolarization The net effect on the mean T axis is to cause it to rotate away from the chilled area, in this instance more anteriorly and toward the right The application of ice to the precordium of thin individuals similarly produces inversion of previously upright T waves in leads recorded over the affected area Cooling the whole body by immersing it in iced water leads to a marked decrease in the oxygen requirements of the tissues and has therefore been employed in recent years in the fields of cardiovascular and neurosurgery, where temporary occlusion of the circulation is essential for the successful repair of certain lesions. The effects of *controlled hypothermia* on the electrocardiogram in man have been studied by several groups of investigators. Hicks et al studied the changes in patients during open heart surgery Gunton et al have published a similar study on a larger group of neurosurgical patients, most of whom had no heart disease and normal preoperative tracings. The observed changes consisted in a slowing of the heart rate, lengthening of the P-R, QRS, and Q-T intervals, flattening or inversion of the T waves and depression of the S-T segment. The continued fall in body temperature was accompanied by progressive depression of the cardiac pacemaker, especially in older patients, with the result that initial sinus rhythm was frequently followed by a variety of supraventricular arrhythmias, notably atrial fibrillation These changes of rhythm usually appeared between 28 and 30°C; only a minority of the patients maintained sinus rhythm throughout the procedure. Atrial fibrillation is abolished by rewarming the body and does not impair subsequent cardiac function. However, reduction of the body temperature below 28°C is attended by risk of ventricular fibrillation or cardiac arrest, particularly in the older age groups and in subjects with cardiac disease. In both groups, temperatures below 30°C should be avoided. Bradycardia, transient atrial fibrillation, depression of the S-T segment, and flattening of the T waves were reported several years ago in a case of accidental immersion in iced water and also in individuals exposed to low temperatures for prolonged periods. *Local application of heat* to the epicardium or precordium shortens the duration of the excited state, and the effects on the tracing are therefore the opposite of those induced by chilling. Heating of the whole body, as by immersion in a hot water bath, produces different changes. These include tachycardia proportional to the rise in temperature, tall P waves, and shortening of the P-R interval, as well as depression of the S-T segment and flattening or inversion of the T waves in some leads The changes in the S-T segment and T waves have been explained partly on the basis of the tachycardia but are probably also due to sympathetic stimulation. Following severe *thermal burns*, depression of the S-T segment has been reported in both infants and adults, probably due to subendocardial injury and necrosis, with liberation of histamine

X-rays. X-ray irradiation has been shown to produce localized areas of myocarditis with corresponding T-wave changes

Electricity. Tracings taken on persons who have been struck by lightning or have been electrocuted may show initial RS-T segment elevation, with subsequent pointed T-wave in-

version and prolongation of the Q-T interval. Subepicardial injury and necrosis have been held responsible for these changes. *The incidence of various arrhythmias, particularly atrial fibrillation,* is fairly high in such cases. *Electroshock therapy,* which is frequently employed in certain psychiatric disorders, usually carries little risk for those *with normal hearts,* but the likelihood of *arrhythmias* is greater in those [illegible] disease. Electrocardiograms taken [illegible] *sinus* [illegible] especially [illegible] P-R interval, and a tendency to right axis deviation. The T and U *waves are of* high amplitude in all leads. Repeat records after a few minutes show considerable flattening of the T waves which *may* become inverted in leads II and III. These T-wave changes resemble those observed after exercise.

TRAUMA

Nonpenetrating Chest Wall Injuries. Most often the *injury is* caused by a blow of varying severity to the anterior chest wall. Severe *myocardial contusion may occur even in* the absence of rib fractures or other evidence of external damage. The injury is usually of the "contrecoup" type, i.e., a blow across the precordium will cause the heart to be displaced backwards until it strikes the vertebral column, and the resulting contusion will be found on the diaphragmatic aspect of the left ventricle. *If the hemorrhage* and injury are confined to the subepicardial zone, the *electrocardiogram* will initially show elevation of S-T segments, *with subsequent pointed* T-wave inversion in the appropriate leads. No Q waves appear, and *the tracing* gradually returns to normal over a period of several weeks. In more severe *injuries* the whole thickness of the ventricular wall may be *involved.* Q waves indicative of *necrosis appear* in addition to the S-T segment and T-wave changes, and the electrocardiographic *picture* is indistinguishable from that of myocardial infarction.

Head Injuries. These are sometimes *responsible* for the onset of atrial fibrillation in subjects who show no evidence of heart disease.

PHYSIOLOGICAL FACTORS

As the sequence of repolarization is easily modified by numerous *factors,* both physiological and pathological, caution should be exercised in the interpretation of tracings which [illegible] occur with *respiration or changes in posture.* A certain number of healthy subjects with a low diaphragm and a vertical or semivertical heart may show T-wave inversion in leads II and III in the erect or sitting position. Elevation of *the diaphragm induced* either by recumbency or by full expiration causes the T waves to become tall and upright *in lead II and less inverted* or flat in lead III. In sthenic individuals with horizontally placed hearts, T waves may become *flattened in lead I and* inverted in leads II and *III* on deep inspiration. These changes may be related to rotation of the T axis as well as to altered sympathetic tone.

Hyperventilation frequently produces depression of the S-T segment and flattening or inversion of the T waves in *various* leads. Prolongation of the P-R interval may also occur at times. The underlying mechanism is not fully understood, but it appears probable that the resultant alkalosis, sympathetic overactivity, or lowering of the diaphragm are causative factors.

Depression of the S-T *segment* and reduction in the amplitude of the T waves have been observed *following a heavy meal,* both in normal individuals and in subjects with coronary *artery* disease. Relative myocardial ischemia is probably responsible for these changes.

A sudden fright has been shown to produce tachycardia initially, followed by bradycardia and *progressive lowering, or even inversion,* of the T waves. P-wave changes due to a shift of the cardiac pacemaker are also commonly seen. The sudden onset of these phenomena indicates that they must be mediated by nervous stimuli.

HYPERTROPHY OF CARDIAC WALLS

Atrial Hypertrophy. Hypertrophy of the atria is revealed in the tracing by an *increase* in width or height of the P waves. The *changes are* best seen in the standard leads.

LEFT ATRIAL HYPERTROPHY. This is *characteristically* associated with *mitral stenosis.* The P waves are broadened and notched, but not

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Temperature. If several healthy individuals are given 800 to 1,000 ml of iced water to drink, the chilling effect on the epicardial surface of the posterior wall of the left ventricle manifests itself in a reversal of the direction of the T wave in a majority of cases. As has been explained previously, the cooling of a particular region of muscle prolongs the duration of the excited state, with a concomitant change in the direction of repolarization The net effect on the mean T axis is to cause it to rotate away from the chilled area, in this instance more anteriorly and toward the right The application of ice to the precordium of thin individuals similarly produces inversion of previously upright T waves in leads recorded over the affected area Cooling the whole body by immersing it in iced water leads to a marked decrease in the oxygen requirements of the tissues and has therefore been employed in recent years in the fields of cardiovascular and neurosurgery, where temporary occlusion of the circulation is essential for the successful repair of certain lesions. The effects of *controlled hypothermia* on the electrocardiogram in man have been studied by several groups of investigators Hicks et al studied the changes in patients during open heart surgery. Gunton et al have published a similar study on a larger group of neurosurgical patients, most of whom had no heart disease and normal preoperative tracings. The observed changes consisted in a slowing of the heart rate, lengthening of the P-R, QRS, and Q-T intervals, flattening or inversion of the T waves and depression of the S-T segment. The continued fall in body temperature was accompanied by progressive depression of the cardiac pacemaker, especially in older patients, with the result that initial sinus rhythm was frequently followed by a variety of supraventricular arrhythmias, notably atrial fibrillation. These changes of rhythm usually appeared between 28 and 30°C; only a minority of the patients maintained sinus rhythm throughout the procedure. Atrial fibrillation is abolished by rewarming the body and does not impair subsequent cardiac function. However, reduction of the body temperature below 28°C is attended by risk of ventricular fibrillation or cardiac arrest, particularly in the older age groups and in subjects with cardiac disease. In both groups, temperatures below 30°C should be avoided. Bradycardia, transient atrial fibrillation, depression of the S-T segment, and flattening of the T waves were reported several years ago in a case of accidental immersion in iced water and also in individuals exposed to low temperatures for prolonged periods *Local application of heat* to the epicardium or precordium shortens the duration of the excited state, and the effects on the tracing are therefore the opposite of those induced by chilling. Heating of the whole body, as by immersion in a hot water bath, produces different changes. These include tachycardia proportional to the rise in temperature, tall P waves, and shortening of the P-R interval, as well as depression of the S-T segment and flattening or inversion of the T waves in some leads The changes in the S-T segment and T waves have been explained partly on the basis of the tachycardia but are probably also due to sympathetic stimulation. Following severe *thermal burns*, depression of the S-T segment has been reported in both infants and adults, probably due to subendocardial injury and necrosis, with liberation of histamine

X-rays. X-ray irradiation has been shown to produce localized areas of myocarditis with corresponding T-wave changes

Electricity. Tracings taken on persons who have been struck by lightning or have been electrocuted may show initial RS-T segment elevation, with subsequent pointed T-wave in-

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especially in leads ...
P-R interval, and a *tendency* to right axis deviation The T and U waves are of high amplitude in all leads Repeat records after a few minutes show considerable flattening of the T waves which may become inverted in leads II and III These *T-wave changes* resemble those observed after exercise.

TRAUMA

Nonpenetrating Chest Wall Injuries. Most often the injury is caused by a blow of varying severity to the anterior chest wall. Severe myocardial contusion may occur even in the absence of rib fractures or other evidence of external damage. The injury is usually of the "contrecoup" type, i e., a blow across the precordium will cause the heart *to be displaced* backwards until it strikes the vertebral column, and the resulting contusion will be found on *the diaphragmatic aspect of the left* ventricle If the hemorrhage and injury are confined to the subepicardial zone, the electrocardiogram will initially *show elevation of S-T* segments, with subsequent pointed T-wave inversion in the *appropriate leads No Q* waves appear, and the tracing gradually returns to normal over a period of several weeks In more severe injuries, *the whole thickness* of the ventricular wall may be involved, Q waves indicative of *necrosis* appear in addition to the S-T segment and T-*wave changes*, and the electrocardiographic picture is indistinguishable from that of myocardial infarction.

Head Injuries. These are sometimes responsible for the onset *of atrial* fibrillation in subjects who show no evidence of heart disease

PHYSIOLOGICAL FACTORS

As the sequence of repolarization is easily modified by *numerous* factors, both *physiologi*cal and pathological, caution should be exer- ... in the interpretation of tracings which ...

... occur with respiration or *changes in posture.* A certain number of healthy subjects with a low diaphragm and a *vertical or semivertical* heart may show T-wave inversion in leads II and III in the erect or sitting position. Elevation of the diaphragm induced either by recumbency or by full *expiration causes the* T waves to become tall and upright *in lead II* and less inverted or flat in lead III. In sthenic individuals with horizontally placed hearts, T waves may become flattened in lead I and inverted *in leads II and III on deep inspiration*. These changes may be related to rotation of the T axis as well as to altered sympathetic *tone*.

Hyperventilation frequently produces depression of the S-T segment and flattening or inversion of the T waves in various leads. Prolongation of the P-R interval may also occur at times. The underlying *mechanism* is not fully understood, but it appears probable that the resultant alkalosis, sympathetic overactivity, or lowering of the diaphragm are causative factors.

Depression of the S-T segment and reduction in the amplitude of the T waves have been observed *following a heavy meal*, both in normal individuals and in subjects with coronary artery disease Relative myocardial ischemia is probably responsible *for these changes*.

A sudden fright has been shown to produce tachycardia initially, followed by bradycardia and progressive lowering, or even inversion, of the T waves P-wave changes due to a shift of the cardiac pacemaker are also commonly seen The sudden onset of these *phenomena* indicates that they must be mediated by nervous stimuli.

HYPERTROPHY OF CARDIAC WALLS

Atrial Hypertrophy. Hypertrophy of the atria is revealed in the tracing by an increase in *width or height of the* P waves. The changes are best seen in the standard leads

LEFT ATRIAL HYPERTROPHY This is characteristically associated with *mitral stenosis*. The P waves are *broadened* and notched, but not

waves. High voltage of the QRS complex is a common finding, and intraventricular conduction disturbances are known to occur. The heart tends to assume a vertical position in the majority of cases, causing the electrical axis to rotate to the right. T-wave changes vary from an increase in amplitude in mild cases to frank inversion and depression of the S-T segment in those of greater severity. Thyroidectomy and therapy with antithyroid drugs restore the normal configurations.

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As the sequence of repolarization is easily modified by numerous factors, both physiological and pathological, caution should be exercised in the interpretation of tracings which show isolated T-wave abnormalities in one or more leads. This is illustrated by the variations in the configuration of the T wave which may occur with *respiration* or *changes in posture.* A certain number of healthy subjects with a low diaphragm and a vertical or semivertical heart may show T-wave inversion in leads II and III in the erect or sitting position. Elevation of the diaphragm induced either by recumbency or by full expiration causes the T waves to become tall and upright in lead II and less inverted or flat in lead III. In sthenic individuals with horizontally placed hearts, T waves may become flattened in lead I and inverted in leads II and III on deep inspiration. These changes may be related to rotation of the T axis as well as to altered sympathetic tone.

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lar hypertrophy is associated with right axis deviation. Leads III, aVF, V_5, and V_6 then show the diagnostic changes

Right Ventricular Hypertrophy. The abovementioned criteria can also be applied to the diagnosis of right ventricular enlargement but here they are even less reliable, because the changes are less pronounced Increase in thickness of the wall of the right ventricle may be manifested by the appearance of tall R waves in leads V_3R, V_1, and V_2 The actual configuration may be qR, R, or rsR'. Not infrequently, the voltage is inconspicuous, but the presence of resultant positivity in lead V_1 in such cases provides a valuable diagnostic clue The R/S ratio over the right precordium is therefore greater than unity, and in some cases shows a progressive decrease in successive leads to the left until it becomes less than unity in leads V_5 and V_6, where an rS complex is found This complete reversal of the normal precordial transition is not always present, however Not infrequently one sees a partial reversal only, a qR complex in lead V_1 being followed by rS complexes over the midprecordium, while the R/S ratio again increases towards or above unity in V_5 and V_6. Sokolow and Lyon have shown that right ventricular hypertrophy is probably present if the sum of R in V_1 and S in V_5 or V_6 exceeds 10 5 mm in adults

S-T-segment depression and T-wave inversion occur in the right precordial leads, but these changes are less constant or pronounced than in left ventricular hypertrophy. The duration of the QRS complex is rarely prolonged unless the hypertrophy of the right ventricle is so marked that the thickness of its wall exceeds that of the left ventricle. This is occasionally the case in certain forms of congenital heart disease. The onset of the intrinsicoid deflection may be delayed in leads over the right precordium where the upper limit of normal is considered to be 0 03 sec

The mean QRS axis is deviated to the right and anteriorly to a varying degree, which explains the resultant positivity in leads V_3R, V_1 and V_2, as well as the tall R waves in leads II, III, and aVF and the rS configuration in lead I. It should be added that right axis deviation of even a moderate degree in an adult accompanied by the P-wave changes associated with "P pulmonale" or "P mitrale" is strong indirect evidence in favor of right ventricular enlargement, even though the precordial leads may only show prominent S waves in leads V_5 and V_6.

Ventricular hypertrophy is a process which develops over a period of time with corresponding evolutionary changes in the electrocardiogram. The diagnosis may therefore have to be based on the recognition of early suggestive features and their correlation with the available clinical data. In general, the data are less marked than on the left side.

UNIPOLAR LEADS

INTRODUCTION

The unipolar leads usually recorded in the routine electrocardiogram are *the augmented unipolar limb leads* (aVR, aVL, aVF) and *the unipolar precordial leads* (V_1, V_2, V_3, V_4, V_5, V_6). Many other unipolar leads are possible, of course, but only those mentioned can be considered here *The bipolar leads* in general use are the three standard limb leads (I, II, III) originated by Einthoven many years ago

It is questionable whether any sharp division should be made clinically between unipolar and bipolar leads Most electrocardiograms recorded today in hospitals and in doctors' offices consist of twelve leads, of which three are bipolar and nine are unipolar. As a rule, these tracings are interpreted as a unit with the different leads receiving attention for the particular views they present of the electrical events taking place in the heart Another reason for avoiding too sharp a distinction between the two types of leads is that *all electrocardiographic leads are, of necessity, bipolar* By this is meant that there must be two connections between the electrocardiograph and the body before any potential variations can be recorded. In this sense, then, *all leads are bipolar* Clinically, however, the leads commonly referred to as "bipolar" have electrodes at two points on the body surface approximately equidistant from the heart These points, like the two upper extremities, have

abnormally tall, and the term *P mitrale* has been adopted to describe this configuration. Since the mean P axis tends to be rotated to the left, these changes are usually most evident in leads I and II.

RIGHT ATRIAL HYPERTROPHY. This type is most frequently encountered in chronic lung disease of various types, but is also seen in some forms of congenital heart disease. The mean P vector tends to rotate to the right, approaching +90°, so that leads II, III, and aVF show the characteristic changes which are referred to as *P pulmonale*. The P waves are tall and peaked but not broadened.

Episodes of *acute pulmonary edema* or *pulmonary embolism* are responsible for sudden increases in intraatrial pressure and consequent dilatation which may be reflected by a transient increase in the amplitude or in a widening of the P waves

Left Ventricular Hypertrophy. The electrocardiographic diagnosis of left ventricular enlargement is made chiefly from inspection of the precordial leads, but it should be emphasized that different authorities employ different criteria and that no rigid rules can be laid down. It is probable that the diagnosis is sometimes missed when hypertrophy is in fact present, and vice versa. Nevertheless, certain abnormalities are frequently associated with this condition in the chest leads and should therefore be sought when the tracings are examined.

INCREASED QRS VOLTAGE The increase in mass and thickness of the left ventricular wall gives rise to stronger electromotive forces which are represented by a larger resultant mean vector. Since the S wave in lead V_1 and the R wave in leads V_5 or V_6 are both due to left ventricular activation, increased amplitude of these deflections should be an index of hypertrophy of this chamber. Sokolow and Lyon have suggested the following criteria for the diagnosis. The sum of the S wave in lead V_1 and the R wave in leads V_5 or V_6 (whichever is the taller) should equal or exceed 35 mm, or the amplitude of the R wave in leads V_5 or V_6 should equal or exceed 26 mm. However, a diagnosis based on voltage alone is open to considerable error in either direction since a thin-chested individual with a normal heart may show voltages of this order while an obese or muscular subject may not do so, and yet have left ventricular enlargement. High voltage may also be masked by the insulating effect of emphysema or the short-circuiting action of a pleural effusion. However, the appearance of tall R waves in the left precordial leads in a thick-chested person constitutes evidence in favor of hypertrophy.

S-T-SEGMENT AND T-WAVE CHANGES. The increase in intracardiac pressure affects the whole thickness of the ventricular wall from endocardium to epicardium. The onset of repolarization is delayed in all zones, but relatively less so in the subendocardial region. This results in a partial or complete reversal of the direction of the recovery process as evidenced by a flattening or inversion of the T waves in the left chest leads. There is usually also an associated depression of the S-T segment in these leads due to the presence of early repolarization forces. Reciprocal elevation may be seen in leads V_1 and V_2.

INCREASE IN THE DURATION OF QRS. The time required for depolarization is longer because of the increased thickness of the ventricular wall. The QRS interval may still be within normal limits or may be prolonged up to 0.12 sec, depending on its original duration. The normal septal Q wave in leads V_5 and V_6 is present in the majority of cases.

DELAYED ONSET OF THE INTRINSICOID DEFLECTION This delay may be observed in leads V_5 and V_6 and is also a result of the hypertrophy This criterion is of doubtful value, not only because of the inertia of the recording instrument, but also because the depolarization process spreads tangentially as well as radially. The accepted upper limit of normal values lies between 0.05 and 0 06 sec.

Since the lead axes of V_5 and V_6 lie close to or in the plane of Einthoven's triangle, the changes shown by these leads are also reflected in the standard and unipolar limb leads In the majority of cases of left ventricular hypertrophy the mean QRS axis tends to rotate to the left (and posteriorly). The configurations in leads I, aVL, V_5, and V_6 therefore resemble each other, and left axis deviation is present. In an asthenic individual, however, the mean axis may not deviate from its normal semivertical position In that case, the three standard leads, aVF, V_5, and V_6 show similar features In rare instances, the axis may actually be vertical or exceed +90°, in this case left ventricu-

ends of these resistances to electrodes on the right arm, left arm, and left leg (Fig. 4-23). This simple resistance network was first fully described by Wilson et al (1934) but had been employed by Wilson for several years before publication.

The circuit illustrated in Fig. 4-24 may be analyzed as follows:

$$VR - VT = ri_R \qquad (1)$$

$$VL - VT = ri_L \qquad (2)$$

$$VF - VT = ri_F \qquad (3)$$

where VR, VL, and VF = potentials of right arm, left arm, and left leg
VT = potential of central terminal
r = resistance in each arm of terminal
i_R, i_L, and i_F = currents flowing through the resistances

Add Eqs. (1), (2), (3) to obtain:

$$(VR + VL + VF) - 3VT = r(i_R + i_L + i_F)$$

Kirchhoff's first law states that the sum of the currents meeting at a point in a network must be zero, hence

$$(i_R + i_L + i_F) = 0$$

Therefore

$$VT = \frac{VR + VL + VF}{3} \qquad (4)$$

It should be pointed out that no assumptions are involved in the derivation of Eq (4), which states that the potential of the central terminal, VT, is the mean potential of the three extremities, except that the equal resistances, r, are large compared with the resistance of the electrodes on the three extremities

By assuming that the conditions underlying the Einthoven triangle arrangement are strictly true and that voltages arising in the heart, oriented perpendicular to the frontal plane, do not affect the potentials of the three extremities, it is possible to show that·

$$VR = -\frac{(+I + II)}{3} \quad \text{potential of right arm} \quad (5)$$

$$VL = \frac{+I - III}{3} \quad \text{potential of left arm} \quad (6)$$

$$VF = \frac{+II + III}{3} \quad \text{potential of left leg} \quad (7)$$

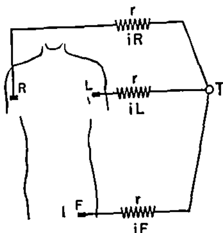


Fig. 4-23. Circuit employed to obtain the central terminal, T, used as the indifferent electrode for unipolar leads. (See text.) (*From Johnston and Willis. Unipolar Electrocardiography.*)

Wilson and associates derived these expressions in a paper published in 1931 and, if they are substituted in Eq (4),

$$VT = \frac{-I - II + I - III + II + III}{3} \qquad (8)$$

It will be observed that the numerator of the right side of this equation is zero, hence VT = 0. This is the theoretical basis for the use of the central terminal as the indifferent electrode

Again it must be emphasized that Eqs (5), (6), and (7) are correct only if the heart is assumed to lie in a homogeneous conducting medium and that the dimensions of the heart are small compared with the equal distances between its center and the symmetrically placed electrodes R, L, and F.

These assumptions, which underlie the Einthoven triangle arrangement, are obviously not strictly true in the human body. For this reason, and also because the frontal plane does not pass through the electrical center of the heart, *the potential of the central terminal (VT) is not zero throughout the cardiac cycle* Nevertheless, its potential variations are smaller than are those of any single point that can be found on the surface of the body, and it is, therefore, *the best indifferent electrode available at this time* Many types of studies, including experiments with subjects immersed in large bodies of water and with cadavers, have supported the view that the central terminal is a fairly good indifferent electrode

If it is assumed that the potential variations of the central terminal are negligibly small, the

potential variations of similar magnitude. Those leads termed "unipolar" are comprised of *an exploring electrode*, placed on the body and connected to the positive terminal of the galvanometer, and *an indifferent electrode*, with a much smaller variation of potential throughout the cardiac cycle, connected to the negative galvanometer terminal. The latter electrode is *the central terminal arrangement* devised by Wilson over 25 years ago and is discussed in more detail below. This indifferent electrode has measurable potential variations, but these are usually negligibly small. Thus, when the galvanometer records the differences in potential between the exploring electrode and the "indifferent" electrode, the record will represent almost entirely the potential variations of the former. It is in this sense that these leads are termed *unipolar*. Since such leads are so extensively used today, it seems worth while to discuss some of the reasons for their development, the premises upon which they are based, and how they function

HISTORICAL BACKGROUND

During the early years of clinical electrocardiography the only leads employed were *the three standard (bipolar) leads of Einthoven*. Many active physicians remember those days and the many problems and uncertainties that arose when additional leads, particularly precordial leads, began to be used. It was not until the late 1920s, and especially the early 1930s, that the usefulness of precordial leads became evident and, for a period of many years, there was no general agreement regarding the technique to be followed when such leads were taken The most important questions involved were· (1) What polarity should be employed? (2) How many precordial leads should be recorded? (3) What sites on the chest wall should be used? (4) What indifferent electrode should be employed?

In 1938 special committees of the American Heart Association and the Cardiac Society of Great Britain and Ireland made recommendations for the standardization of precordial leads These recommendations gradually helped to lessen the confusion in this field, but it is interesting that, in a second supplementary report by the same committee of the American Heart Association in 1943, there was still no specific recommendation relative to the indifferent electrode to be employed. In the years that followed, however, there has been a slow but progressive adoption of the central terminal for the registration of precordial leads by physicians all over the world, so that the so-called unipolar precordial leads (V leads) are almost always recorded today. It is interesting that some physicians, especially in England, still use other indifferent electrodes, particularly an electrode on the right arm, for the registration of chest leads.

Most electrocardiographers would agree that precordial leads may be considered *semidirect leads* and give information similar to that which would be obtained from direct leads in which electrodes are placed on the surface of the heart *Direct leads* are obviously impractical for ordinary clinical use but, when they are obtained in experimental animals (or occasionally in patients with hearts exposed during surgery), it is found that the potential variations are roughly 20 times greater than those in ordinary limb leads, and for this reason the indifferent electrode may be placed anywhere on the surface of the body remote from the heart without appreciably altering the tracing obtained In the case of precordial (semidirect) leads this is not true, since the potentials on the chest wall are much smaller (one-tenth or less) than those at the surface of the heart and may not be much greater than those of the extremities or other points on the surface of the body some distance from the heart This means that precordial leads may be altered in size and form when the indifferent electrode is placed at different points on the body and, under these circumstances, may function more like bipolar rather than unipolar leads Wilson became aware of this situation in the late 1920s, and developed the "central terminal" arrangement largely to provide what he believed would be a better indifferent electrode for the registration of precordial electrocardiograms He firmly believed that tracings taken from the precordium would be of more clinical value if general agreement could be reached on the indifferent electrode used for this purpose

TECHNIQUE

The central terminal is created by connecting together three fairly large equal resistances, *r*, at a common point and attaching the other

Substituting in Eq (11),

$$2aVR = 2VR + VR$$

and

$$aVR = \tfrac{3}{2}VR$$

A similar relationship, of course, exists between aVL and VL and aVF and VF.

It was pointed out above that the potential of the central terminal, $VT = (VR + VL + VF)/3$, has the mean potential of the three extremities only if the equal resistances in the arms of the terminal are large compared with the resistance of the electrodes on the extremities This is also true of the modified terminal employed for registration of the augmented extremity leads, but some explanation of the reasons for this statement should be given.

Suppose, as has been suggested in the past, the resistances in question are reduced to zero. In other words, electrodes on the three (or two) extremities are connected together with wires of negligible resistance. Under these circumstances, Eqs (4) and (9) will be valid only if the resistances of three (or two) electrodes happen to be equal, and this is not likely to occur very often Large resistances in the central terminal are necessary, then, so that even when the resistances at the electrodes are widely different the effect of these inequalities is not important, and the terminals serve as good averaging networks. These matters were emphasized by Bryant et al and by Rappaport and Williams in 1949

When Wilson first started to use the central terminal, resistances of 25,000 ohms were employed, but a-c interference was such a serious problem that the resistances were reduced to 5,000 ohms, and this value was kept for a number of years Newer techniques, however, particularly the general practice of grounding the patient with an electrode on the right leg and the development of differential amplifiers, have minimized the difficulties with stray a-c interference to such an extent as to make possible trouble-free use of considerably higher resistances, 50,000 ohms or more, in the terminals Many modern electrocardiographs use resistances of this size

In the above discussion, attention has been devoted largely to technical considerations, primarily relating to the central terminal as an electrical averaging network and why it has been useful in so-called unipolar electrocardiography It was suggested at the outset that it may be unwise to draw sharp distinctions between the bipolar limb leads (I, II, and III) and the unipolar extremity leads (aVR, aVL, and aVF) or the unipolar precordial leads, and, in the following brief analysis of the behavior of all of these leads, as reflected by their lead fields, this point of view receives support. The behavior of any type of lead becomes clear if the character of its associated lead field is known, and fortunately this is easy to determine, at least in approximate fashion.

THE LEAD FIELD

Since the idea of the lead field may be unfamiliar to some readers, a few comments regarding this concept and its usefulness are in order. It may be defined as *the current field that exists if a battery of suitable voltage is connected to the two electrodes of a lead so that unit current passes into the body* It will be observed that, to obtain the lead field, the procedure ordinarily employed in electrocardiography is reversed; that is, instead of measuring potential difference, produced by electromotive force (emf) arising in the heart, between electrodes on the body by a suitable instrument, an emf is connected to the electrodes and this causes current to flow within the body, including the heart, and this current field is the lead field. By means of the reciprocity theorem of Helmholtz it may be shown that the direction and intensity of the lead field passing through the heart determines the behavior of the lead with respect to voltages produced within this organ Thus, emf, at any point in the heart, that is oriented in the direction of the lead field at that point contributes maximally to the voltages appearing at the electrodes of the lead, while emf in the heart oriented at right angles to the lead field contributes nothing to the lead voltage Figure 4-25 illustrates the lead field for standard lead I. It will be observed that its general direction through the heart is transverse, and this is, of course, why lead I depicts primarily the horizontal or transverse component of cardiac voltages

One might properly ask how a lead field, like that illustrated in Fig 4-25, is obtained. There is no direct method for the estimation of the lead field in the heart muscle or elsewhere within the body Fortunately, however, since the spatial relationship between the electrodes of any lead and the heart are always known, the approximate pathway of currents that will

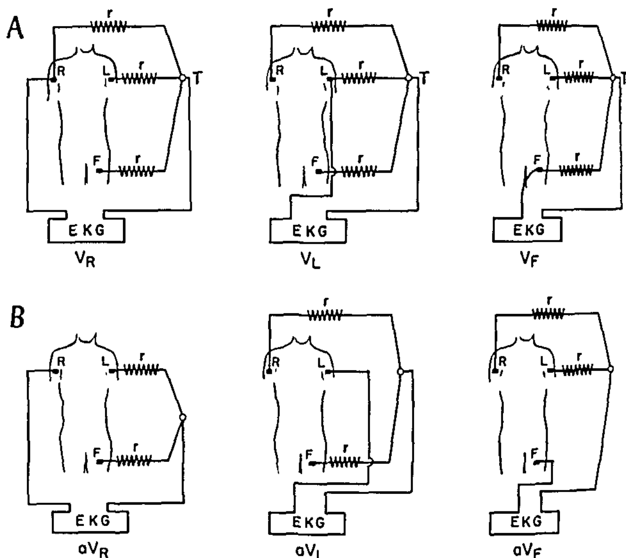


Fig. 4-24. A Circuits used to record unipolar extremity leads VR, VL, and VF. B. Circuits used to record augmented unipolar extremity leads aVR, aVL, and aVF.

potential variations of any point on the surface of the body, including the three extremities, may be recorded by placing an exploring electrode at this point and connecting the other wire from the recording instrument to the central terminal. It is customary to make the connections so that positivity of the exploring electrode with respect to the central terminal yields an upward deflection in the electrocardiogram. When this procedure is carried out with the exploring electrode attached to electrodes on the three extremities, the unipolar extremity leads, VR, VL and VF (Fig. 4-24A) are recorded These tracings are often rather small, and this has led to the general adoption of a modified technique, first described by Goldberger, which gives records of the same form but 50 per cent larger than the ordinary unipolar extremity tracings. These are called the augmented extremity leads, aVR, aVL and aVF, and are obtained by disconnecting the central terminal from the electrode on the extremity the potential variations of which are being estimated (Fig. 4-24B).

The relationship between the ordinary and the augmented extremity leads may be demonstrated as follows.

Referring to the first figure in 4-24B, it will be seen that

$$VT = \frac{VL + VF}{2} \quad (9)$$

Therefore

$$aVR = VR - \frac{VL + VF}{2} \quad (10)$$

Multiplying Eq (10) by 2,

$$2aVR = 2VR - (VL + VF) \quad (11)$$

But since $VR + VL + VF = 0$,

$$(VL + VF) = -VR$$

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and

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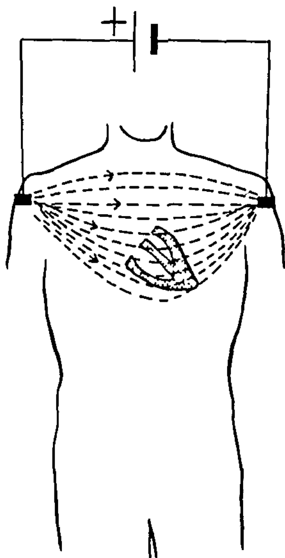


Fig. 4-25. The dashed lines passing through the body, including the heart, represent the lead field of standard lead I. The battery, connected to electrodes on the right and left arms, has a voltage of proper magnitude to cause unit current to flow through the body (See text)

flow through the heart when a battery is connected to the terminals of a lead (i.e., the lead field) may be determined in any desired plane with a little intelligence and imagination It is assumed that the tissues within the body may be considered of uniform conductivity This is not strictly true, but the errors introduced by this assumption are not great. The lead field may not only be used to analyze the behavior of any type of lead, but it is also helpful in the design of new lead systems that may be valuable for special purposes. The reader interested in more details about theoretical and practical aspects of the lead field is referred to articles by McFee and Johnston.

Unipolar Limb Leads. The lead fields associated with leads VR, VL, and VF, and aVR, aVL, and aVF, are shown in Fig. 4-26. In each part of this figure it is assumed that the positive pole of the battery is connected to the electrode on the extremity the potential of which is to be measured. Thus, in Fig. 4-26A, current flows from the battery into the body through the electrode on the right arm and leaves the body *in equal amounts* through the electrodes on the left arm and the left leg. The curved dotted lines represent these currents, and the complete or resultant lead field through the heart is the vector sum of these at any point and is given by the solid lines It will be observed that this lead field for aVR (or VR) is oriented nearly parallel to a straight line from the center of the heart to the right shoulder, and this means, of course, that this lead is most sensitive to cardiac voltages with similar orientation. Since leads aVR and VR are the same, except that in the latter the electrode on the right arm is connected to the central terminal through resistance *r* and in the former this connection is removed, it is clear that the lead fields for both are identical except that the current flowing through the body (and the heart) is only two-thirds as great with lead VR as with aVR This difference in the strength of the lead field is the reason, as was stated in the previous section, why the augmented unipolar extremity leads are 50 per cent larger, but otherwise the same, as the ordinary unipolar extremity leads.

In Fig 4-26, parts B and C are illustrations of the lead fields for the other two unipolar extremity leads, and the same statements made in connection with aVR and VR, with appropriate changes in terms, apply equally to these leads To avoid confusion and misunderstanding of the role played by the lead field in the foregoing analysis and in further discussion below, it must be emphasized that its use does not alter in any way the technique employed in routine electrocardiography. The lead field is simply a device to explain how leads behave, and it is obtained by imagining that the electrocardiograph is temporarily disconnected from the electrodes of any lead and is replaced by a battery of suitable size When this is done, the approximate direction of paths of currents flowing through the body, including the heart, may be determined, and this cur-

rent field is the lead field. For the purpose of this discussion the only part of *the lead field* that is important is the region that passes *through the heart*.

Precordial Leads. Since the lead field idea may be employed to analyze the behavior of leads of any type, it seems logical to point out here the application of this concept to precordial leads. First, one might ask, what kind of lead field would be associated with an *ideal* unipolar lead? Here the indifferent electrode would be at infinity and the lead field would consist of paths of current radiating in a uniform radial fashion from the exploring electrode (Fig. 4-27A). In this same figure (B and C) the lead fields for an anterior unipolar precordial lead in the sagittal and transverse planes respectively, are shown, and in Fig. 4-27D the lead field for the same precordial lead with the leg employed as the indifferent electrode (a CF lead) is illustrated It will be noted (in Fig. 4-27, parts B and C) that the lead field radiates from the exploring electrode in a fairly symmetrical fashion It is also clear that, although there is some curvature of the field, the general direction through the heart is anteroposterior, and for this reason this lead will record cardiac emf oriented primarily in this direction. Finally, since the lead field is *more* intense through the anterior regions of the heart than it is posteriorly, it is obvious that a given voltage located *in the anterior aspect* of the heart will contribute more to the tracing obtained than would an emf of the same size and orientation situated in the posterior part of this organ. There has been considerable controversy concerning this matter, some electrocardiographers maintaining that all parts of the heart contribute equally to tracings obtained from the precordial area. The lead field analysis indicates that *this cannot be true*. If the heart happens to be unusually close to the chest wall and to the exploring electrode, this proximity effect due to the flare of the lead field will be more marked than if the heart is some distance from the surface of the chest. The lead field of the CF lead, illustrated in Fig 4-27D, shows less symmetry and curvature of a different character when compared with the field of the unipolar chest lead (with the central terminal as the indifferent electrode) shown in Fig 4-27B. In both instances the

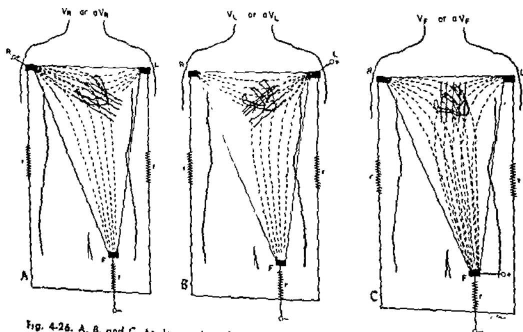


Fig. 4-26. A, B, and C As drawn, these figures show the connections for the unipolar extremity leads VR, VL, and VF, respectively, but, in each instance, the augmented unipolar extremity lead would be recorded if the resistance, r, connecting electrodes R, L, and F to the central terminal, were omitted The dashed lines represent equal amounts of current flowing from one extremity (whose potential is being estimated) to the other two, and the solid lines show the actual current flow, i e, the lead field, through the heart. (See text)

general direction of the lead field through the heart is anteroposterior, but with the CF lead more of the field is oriented in a vertical direction, and these differences in the fields explain the variation seen when the unipolar precordial leads (V leads) are compared with CF leads. It should be mentioned that it is possible to design a lead which will record the emf with complete fidelity, irrespective of its location in the heart. To accomplish this, the lead must have a lead field, like that shown in Fig 4-27E, where the current field consists of strictly parallel and uniform lines of flow, here oriented in an anteroposterior direction. To obtain such a lead field, grid arrangements employing many small uniformly distributed electrodes, each connected through l rge equal resistances to a single common terminal, are placed over the entire precordial area and over the left posterior chest behind the heart (Fig 4-27E). This type of lead not only records the emf in the posterior part of the heart just as well as voltages in the anterior aspect of that organ but, since the lead field is strictly anteroposterior in direction, it will record the sagittal component of all cardiac voltages (having such a component) with accuracy. For these reasons, it is an ideal lead to obtain the sagittal component of the cardiac voltages for vectorcardiography or other purposes, and its construction and use have recently been described by Reynolds et al.

It will be impossible to discuss changes occurring in the unipolar extremity and pre-

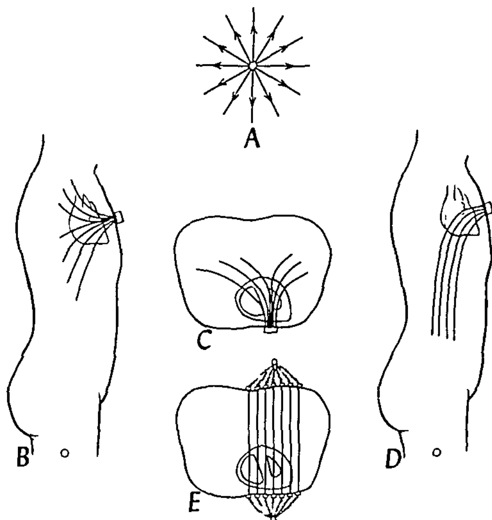


Fig. 4-27. A. The lead field for a perfect unipolar lead B The lead field for an interior unipolar chest lead shown in a sagittal plane through the heart. C Same as (B) but shown in a horizontal plane through the heart. D The lead field for an anterior chest lead with the electrode on the left leg employed as the indifferent electrode. The lead field for this CF lead is shown in a sagittal plane through the heart. E. Multiple-electrode grid arrangement necessary to produce a uniform lead field oriented in an anteroposterior direction. (See text)

cordial leads in detail in this section, since this would involve much of the material included in a text on clinical electrocardiography. The authors will attempt, however, in the discussion below to point out the special properties, fields of usefulness, and relationships between these leads, integrating this material as closely as possible with the previous paragraphs.

BEHAVIOR OF UNIPOLAR EXTREMITY LEADS

The key to the behavior of the unipolar extremity leads has already been given in the discussion of their lead fields. Thus, lead aVR records primarily cardiac emf oriented along a line from the center of the heart to the right shoulder, lead aVL from the center of the heart to the left shoulder, and lead aVF from the center of the heart to the left thigh.

In most normal subjects and in many patients with heart disease the general pathways of excitation of the atria and the ventricles are along the anatomic axis of the heart in a base-to-apex direction or, in other words, the mean vectors of the P wave and QRS complex are oriented downward and to the left The same situation is usually true of the vector representing recovery or repolarization of the ventricular muscle; therefore, it is to be expected that, in lead aVR, the P waves, QRS complexes, and T waves will be primarily downward deflections This is, of course, ordinarily true Another way of expressing this, in connection with the QRS complex, is to state that this complex in lead aVR is primarily negative because the base of the heart faces the right shoulder and that this region reflects potentials existing in the cavities of the two ventricles. These potentials are known to be almost entirely negative unless intraventricular block is present.

Although the form of lead aVR is remarkably constant, much more so than that of leads aVL or aVF, it is not unusual to see primarily negative QRS complexes in this lead that begin with a small R wave and even more often terminate with a sizeable R wave The latter is common in normal electrocardiograms and is usually a prominent feature of the tracings when right bundle branch block or right ventricular hypertrophy are present. These findings indicate that *lead aVR does not record pure cavity potentials*, although it is usually strongly influenced by them. When the form of the QRS complex in this lead departs considerably from the expected cavity potential, it suggests that the heart is rotated either on an anteroposterior axis or a transverse axis (with the apex of the heart displaced forward or backward) or that rotations of both types have occurred Changes of this kind in lead aVR have been used by many electrocardiographers to estimate rotation of the types mentioned. Unfortunately, there is usually little besides this electrocardiographic evidence to suggest such rotation

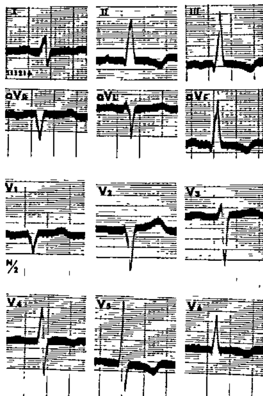


Fig 4-28. Electrocardiogram illustrating a vertical position of the heart The limb leads do not show left axis deviation, but the chest leads (taken at half-normal sensitivity) point clearly to left ventricular hypertrophy. (See text)

One might properly inquire if the potentials within the cavities of both ventricles influence the form of lead aVR or if the effects from one of these chambers predominates over those of the other. It has been felt by some that the QRS complex in lead aVR is controlled primarily by cavity potentials within the left ventricle, but there is conflicting evidence on this point. For example, were this statement true,

the QRS complex in lead aVR in the presence of left bundle branch block should begin with a definite R wave, since the cavity of the left ventricle is initially positive when this block is present. Actually, this rarely if ever happens. The complex in question is often of low voltage but is usually initially negative and may or may not show a final upward deflection.

The form of the QRS complexes in leads aVL and aVF varies greatly, often in a reciprocal fashion. Thus, in many tracings, both normal and abnormal, these complexes in lead aVL may resemble those found in precordial leads taken over the left ventricle (i.e., leads V_5 and V_6) *while those in lead aVF are like those* seen in leads taken over the right ventricle (i e , leads V_1 and V_2). Occasionally the reverse is true, and often the QRS deflections in one of these leads resembles those seen over either the right or left ventricle, and the other shows small deflections. Wilson noticed and was interested in these similarities primarily because he believed them to point out relationships between the limb and chest leads and to explain some peculiarities in the former that are otherwise difficult to understand He first discussed these relationships in 1941, and in 1944 he suggested *that they be described by* certain electrical positions of the heart

The *transverse or horizontal position* means that the QRS complexes in lead aVL resemble those seen in precordial leads obtained from regions close to the left ventricle, and the complexes in lead aVF are similar to those taken over the right ventricle The opposite relationship is found in the *vertical position*, and the other positions described lie between these two extremes Thus, in the *semivertical position*, the QRS complexes in lead aVL are small, and those in lead aVF are like those found in chest leads from the left ventricle. A tracing illustrating a vertical heart is shown in Fig 4-28. It will be observed that the limb leads do not show left axis deviation, although it is clear from the chest leads that left ventricular hypertrophy is present This is due to the vertical heart here It is clear that the position of the mean electrical axis of the QRS complex in the frontal plane (the plane of the limb leads) depends not only on hypertrophy of the right or left ventricle but also on the electrical position of the heart. When the heart is abnormal and enlargement or dilatation is present, the organ is usually in the transverse or semitransverse position. Under these circumstances, there is correlation between findings in limb and precordial leads. That is, when the latter indicate right or left ventricular hypertrophy, the limb leads show right and left axis deviation respectively, and when the chest leads point to right or left bundle branch block, the limb leads show the usual changes with deviation of the mean electrical axis to right or left. Only in occasional tracings where the heart is in the semivertical or vertical position do discrepancies between the information suggested by the limb and chest leads appear. These *facts led Wilson (1941) to* conclude that, "The exact position of the mean electrical axis of the heart is of no clinical importance." He was, of course, referring here solely to the electrical axis in the frontal plane. A very important corollary of this discussion is that precordial leads provide far more reliable evidence pointing to right or left ventricular hypertrophy or to the ventricle involved in bundle branch block than do the limb leads.

If one approaches these matters from the standpoint of the lead fields of lead aVL and aVF, it is clear that, in the case of the vertical *position of the heart, the lead field* of the former must pass through the ventricles in the same general fashion as does that of a unipolar chest lead with the exploring electrode over the right ventricle; and the lead field of lead aVF must be similar to that of a chest lead over the left ventricle This can be true only if there is actual mechanical rotation of the heart in a clockwise direction (viewed from the apex) about its long axis and probably some rotation about the transverse axis with the apex displaced anteriorly as well As mentioned in connection with the discussion of *lead aVR, rotation of the heart* about its axes may be suspected from electrocardiographic findings, but often there is little or no other evidence to support such suspicions. This is particularly true with respect to rotation about the long axis of the heart. Under such circumstances, chest films and fluoroscopy usually fail to confirm the impression gained from the electrocardiogram, probably because considerable rotation of this kind may occur without altering the shape of the cardiac silhouette or modifying the character of its border movements very greatly.

The lead field associated with lead aVF has special properties that make this lead of particular interest and value. In Fig. 4-26C it will be seen that the lead field of lead aVF is oriented in a nearly vertical direction, and the lines of current flow are approximately parallel. This means that *lead aVF records cardiac voltages (or their components) that are directed vertically and is unresponsive to the emf directed in a purely transverse or anteroposterior (sagittal) direction.* In other words, lead aVF is a good orthogonal lead for the vertical component of

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tical (or

grams in the frontal or sagittal planes. If these *vector figures are to be accurate,* leads providing good recording of the transverse and sagittal components of the cardiac emf must, of course, be combined with lead aVF. The multiple-electrode grid arrangement referred to above (Fig 4-27E), or some similar type of lead system, will provide a good sagittal component, and a similar grid of electrodes in the two axillae, or lead I corrected by suitable additional electrodes, may be used for the transverse component *It is quite possible that simple techniques, practical for routine clinical use, will soon be available for obtaining the three orthogonal components of cardiac voltages with great accuracy.* Thus, data now obtained in more complicated form in the six usual limb leads would be presented in two electrocardiograms—the transverse *or x* lead, and the vertical *or y* lead These same leads would, of course, be available for vectorcardiography if the physician preferred this type of presentation Since the sagittal lead (*z*) under consideration records, just as anterior precordial leads do, cardiac voltages oriented primarily in an anteroposterior direction, one might properly inquire if the usual chest leads might not be discarded and clinical electrocardiography be reduced to the three orthogonal leads. For routine purposes and for many other situations, the three tracings mentioned might well suffice and provide a complete electrocardiographic survey. Precordial leads might be necessary only with small localized lesions such as small infarcts located on the accessible surfaces of the ventricles. The advantages of such simplification of clinical electrocardiography are too obvious to need further comment. Among other things, this discussion points to the importance of a careful study of a good sagittal lead.

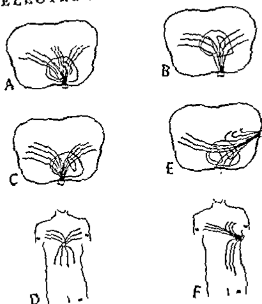


Fig. 4-29. A. and B. The lead field of an anterior unipolar chest lead when the heart is close to anterior chest wall (A) and centrally placed in the chest (B). C. and D. Lead field of a strictly anterior unipolar chest lead in *horizontal and frontal planes, respectively. E. and F. Lead field for chest lead* V_6 in horizontal and frontal planes, respectively. (See text.)

BEHAVIOR OF UNIPOLAR CHEST LEADS

As was mentioned earlier, *unipolar precordial leads give information similar to that seen in tracings obtained by direct leads located on the surface of the ventricles immediately beneath the site of the precordial electrode.* The lead fields of the two will be similar. If the heart happens to lie close to the skin surface (Fig. 4-29A), the lead fields of the precordial and the underlying direct leads will be very much alike, whereas if the organ is some distance from the skin (Fig. 4-29B), the resemblance will be less marked. In the latter instance, *there is still some concentration of the lead field in anterior portions of the myocardium* and, as mentioned previously, this means that cardiac voltages oriented parallel with the lead field in this part of the heart contribute more to the electrocardiogram that is recorded than do similarly oriented voltages of the same size located

in posterior regions of the heart. When the heart is very close to the surface of the chest, the above statements are, of course, true to an even greater degree.

The above matters have been mentioned because, although they are rarely considered in discussions of precordial leads and their interpretation, they are of considerable practical importance. They almost certainly help to explain differences in the size of initial R waves found in tracings taken over the right side of the precordium and the great variations in the amplitude of R waves encountered in left precordial leads; these are quite independent of hypertrophy and other myocardial abnormalities. With *right ventricular hypertrophy*, this chamber is often closer to the surface of the chest than usual, and it is possible that the large R waves, commonly present in right precordial leads under these circumstances, are caused by the close proximity of the exploring electrode to the right ventricle, as well as by its hypertrophy. It is difficult, of course, to estimate with accuracy the distance between the chest electrode and the surface of the heart, and this distance varies not only because of differences in the position of the heart within the thorax but also as a result of variations in the thickness of the subcutaneous tissues Nevertheless, the electrocardiographer should keep these matters in mind, since they may help him in proper interpretation of many tracings. Thus, it is not uncommon to see records obtained from individuals whose hearts are normal and yet R waves, seen in leads taken over the left ventricle, may be so large that, if one follows some of the suggested rules, left ventricular hypertrophy may be suspected Situations of this kind are particularly frequent in old patients with long, tortuous aortas which have caused *the heart to become very transverse in position* and caused the left ventricle to closely approach the chest wall. Some of these individuals are undernourished and have little subcutaneous tissue, so that the exploring electrode in the 5th and 6th positions may be unusually close to the left ventricle.

Another large group of patients, many without organic heart disease, are those unfortunate individuals with marked *pulmonary emphysema.* Electrocardiograms taken on such patients are frequently of unusual outline, and the precordial leads often show a broad transitional zone of QRS complexes displaced well to the left and, even in the 5th and 6th positions, tracings of the type usually found over the left ventricle are not present. Some of these changes are undoubtedly due to rotation of these hearts about the long axis, with the left ventricle more posteriorly placed than usual, but these hearts also tend to be centrally placed in the thorax with all surfaces a considerable distance from the chest wall. Under these circumstances the lead field of any precordial lead will show that the lines of current flow through the heart are more nearly parallel than is usually the case, and this must be an important factor in causing some of the peculiarities mentioned. The precordial leads in these patients represent primarily averages or summations of the emf acting in the entire heart with proximity effects due to nearness of the exploring electrode to certain parts of the heart playing a relatively minor role.

If the pathway of excitation or the direction of the activation wave within the ventricular muscle is parallel to the lead field of any precordial lead, it is clear that the QRS complexes in this lead will be larger than if the wave of excitation and the lead field are not similarly oriented There can be no question about the correctness of this statement, but unfortunately complete and accurate information is lacking regarding both of these quantities and how differences or similarities in their directions in certain parts of the ventricles may modify the QRS complexes Nevertheless, some discussion of these relationships may be worth while

The lead fields of unipolar precordial leads are determined almost entirely by the locations of the precordial electrode and the spatial relationships of this electrode, whether it be placed at a site over the right ventricle (i e, 1st or 2d position) or further to the left over the left ventricle (i.e., 5th and 6th position), *and the areas within the body where the right and left arms and the left leg join the torso* This means that the general form of the lead field for any given chest lead is fairly constant for all human subjects but, since the position of the heart within the thorax varies considerably in normal subjects and varies especially in patients with heart disease, this general tendency for the lead fields to be of constant

form does not mean that the fields pass through the ventricles or other parts of the heart in the same direction or with the same curvature in different individuals.

It will not be possible to discuss the lead fields for all six of the usual unipolar precordial leads, but the field associated with one located anteriorly (in the midsternal line midway between the 1st and 2d positions) and the lead field of lead V_6 (located in the left midaxillary line) will be considered in some detail. Figure 4-29 (A and D) shows the approximate lead field of the former in a transverse plane through the heart and in the frontal plane respectively, and Fig 4-29 (E and F) illustrates the field for lead V_6 in the same planes Because it is more centrally located with respect to the two shoulders and the left thigh, the lead field of the anterior chest lead shows more symmetrical lines radiating from the exploring electrode than is true of the field of lead V_6 Furthermore, although it shows considerable curvature, the general direction of the field of the former will be in an anteroposterior direction through the heart, while the latter is primarily transverse in its orientation Thus feature of the lead fields of the lateral chest leads, especially lead V_6, explains why these leads so often resemble leads I and aVL. Their lead fields are similar in orientation. The similarity between these tracings is great when the heart is in the *horizontal* or *semihorizontal electrical position* since, under these circumstances, the left shoulder region and all of the left midaxillary region are close to the left ventricle and reflect the potential variations at its surface With the *vertical position*, on the other hand, right ventricular potentials dominate the left shoulder region and are present in lead aVL, while the lower position of the exploring electrode in the 6th position causes lead V_6 to show potential variations of the left ventricular type

The pathways of excitation through the interventricular septum and the free walls of the ventricles have been studied extensively in recent years, but there still is insufficient information about the character of this process to permit the explanation of many of the waves of the QRS complexes by correlating the direction of the excitation wave with the lead field of any precordial lead. As will be mentioned below, there is some indirect evidence on this point which may help to make the general pathway of excitation, especially in the left ventricle, more clear.

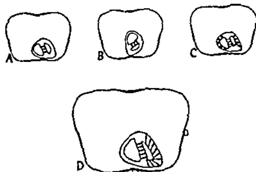


Fig. 4-30. A. The arrows indicate the early excitation of *the left side of the interventricular septum.* This emf is responsible for physiological Q waves in leads I, aVL, and chest leads from sites over the *left ventricle.* B Although this figure illustrates it poorly, the heart shown in (A) is supposed to be rotated about its long axis so that the right ventricle is located more anteriorly and the left ventricle more posteriorly. Under these circumstances, the emf due to early activation of the septum may be oriented in a PA direction or slightly right-to-left (as shown) and physiological Q waves will not be present. C. This figure illustrates the classical idea of excitation of the septum and the free walls of the ventricles The former is activated from both sides, and the latter in a radial fashion from within outward. D This figure shows the type of excitation that may exist in the presence of left bundle branch block The septum is activated from right to left and the pathway of excitation through the free wall of the left ventricle may follow the oblique course indicated by the arrows (See text)

It has been known for many years that, with normal intraventricular conduction, *excitation in the ventricles begins on the left side of the septum, causing an initial emf, usually oriented from left to right and anteriorly* This initial vector is responsible for "physiologic" Q waves often seen in leads I and aVL, and in precordial leads taken over the left ventricle It also causes the first part of the initial R waves frequently seen in tracings taken over the right ventricle. The balance of these R deflections is believed to be caused by the excitation wave passing from within outward through the free wall of the right ventricle. Figure 4-30A illustrates, in a *transverse section through the ventricles*, the direction of the activation wave caused by physiological initial excitation of the left side of *the septum.* It should be pointed out here

in posterior regions of the heart. When the heart is very close to the surface of the chest, the above statements are, of course, true to an even greater degree.

The above matters have been mentioned because, although they are rarely considered in discussions of precordial leads and their interpretation, they are of considerable practical importance. They almost certainly help to explain differences in the size of initial R waves found in tracings taken over the right side of the precordium and the great variations in the amplitude of R waves encountered in left precordial leads; these are quite independent of hypertrophy and other myocardial abnormalities. With *right ventricular hypertrophy*, this chamber is often closer to the surface of the chest than usual, and it is possible that the large R waves, commonly present in right precordial leads under these circumstances, are caused by the close proximity of the exploring electrode to the right ventricle, as well as by its hypertrophy. It is difficult, of course, to estimate with accuracy the distance between the chest electrode and the surface of the heart, and this distance varies not only because of differences in the position of the heart within the thorax but also as a result of variations in the thickness of the subcutaneous tissues Nevertheless, the electrocardiographer should keep these matters in mind, since they may help him in proper interpretation of many tracings. Thus, it is not uncommon to see records obtained from individuals whose hearts are normal and yet R waves, seen in leads taken over the left ventricle, may be so large that, if one follows some of the suggested rules, left ventricular hypertrophy may be suspected Situations of this kind are particularly frequent in old patients with long, tortuous aortas which have caused *the heart to become very transverse in position* and caused the left ventricle to closely approach the chest wall Some of these individuals are undernourished and have little subcutaneous tissue, so that the exploring electrode in the 5th and 6th positions may be unusually close to the left ventricle.

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tracings showing *left bundle branch block*, there are peculiarities in the precordial leads that are very difficult to understand if the excitation wave spreads through the wall of the left ventricle in the simple radial fashion shown in Fig 4-30C. Thus, with left bundle branch block, large, broad S waves are encountered in tracings obtained with anterior precordial leads, and considerably smaller broad R waves are found in lead V_6. Since the large S waves must arise to a large extent in the left ventricle, which is a considerable distance from the location of the anterior chest electrode, one may properly inquire why these S waves are so much larger than are the R waves in lead V_6, where the exploring electrode

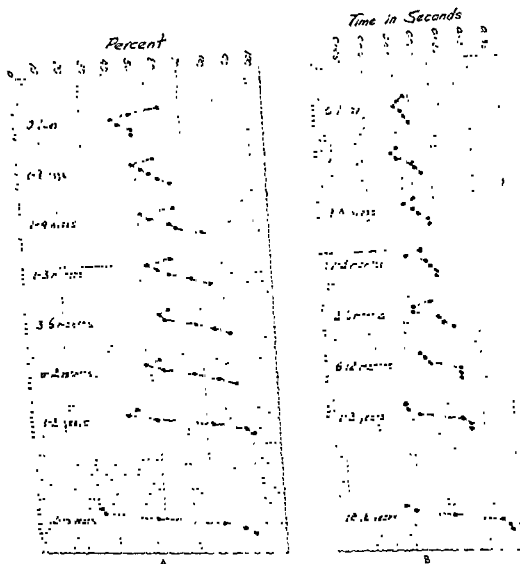


Fig. 4-31. A. The amplitude of intrinsic deflection in unipolar precordial leads expressed as a percentage of RS in the same lead Each group of six points represents measurements for each of the precordial leads V_1 through V_6 Note the progressive changes during the period of early infancy and the comparison with the adult pattern attained at the age of about 12 to 16 years. B The time of onset of the intrinsic deflection in precordial leads measured from the beginning of QRS in simultaneous standard lead I Each group of six points represents measurements for each of the precordial leads V_1 through V_6. Note the progression of changes during early infancy and the relation to the adult pattern reached between age groups of 12 to 16 years. (Courtesy of Charles C Thomas.)

that, if there is *rotation of the heart about its long axis,* causing the right ventricle to occupy most of the anterior portion of the heart and the left ventricle to lie posteriorly (Fig. 4-30B), the early septal emf will be oriented in a posteroanterior direction and not from left to right The latter means that the "physiologic" Q waves mentioned above will vanish and it may also mean that the early septal emf contributes more to the initial R waves than usual, since these voltages are more nearly parallel with the lead fields of anterior chest leads than is ordinarily the case. With *complete and incomplete left bundle branch block,* physiologic Q waves are also absent due to activation of the septum in a right-to-left direction The foregoing matters have been discussed, since some electrocardiographers have implied that the absence of physiologic Q waves indicates the presence of incomplete left bundle branch block, even when the QRS interval is normal. The authors do not agree with this view

The initial period of septal excitation mentioned above exists for only a few hundredths of a second before activation starts on the right side of the septum, probably near the base of the anterior papillary muscle, and very shortly thereafter the Purkinje network lining the endocardial aspect of both ventricles is excited and activation of the free walls of these chambers begins. Until recently, it was believed that the ventricular muscle was a syncytium with no Purkinje fibers penetrating for any significant distance, consequently, a simple radial spread of excitation from within outward was thought to exist in the free walls of the ventricles, the septum (except for the earlier activation of the left side) was assumed to be excited from both sides (Fig 4-30C) Experimental studies by Kennamer et al , who used intramural electrodes, are interpreted to indicate, however, that the subendocardial layer of the left ventricle is activated very rapidly and in many different directions, and spread of the excitation wave from within outward occurs only in the subepicardial layers of this chamber. This general concept is supported by work of Durrer and van der Tweel and by Sodi Pallares et al. However, Scher et al , using a somewhat different technique, have presented evidence which supports the original idea that the excitation wave may be considered to pass through the entire wall of the left ventricle in a roughly radial fashion from within outward. Correct interpretation of changes in the form of the QRS complexes in precordial leads, especially in connection with myocardial infarction, depends to a large degree on the actual course of excitation in the left ventricle, and further studies which will settle the questions raised above are badly needed Although the authors have done no experimental work relating to the excitation of the left ventricle, and therefore should have no good reason for expressing an opinion about its character, they are inclined to agree with the views of Scher et al. at the moment. If the subendocardial muscle actually contributes little or nothing to the QRS complex, recorded by direct or precordial leads, as the new hypothesis demands, one would hardly expect the excellent correlations between electrocardiograms and pathologically proved infarcts found in the experimental studies of Wilson et al. and in the extensive observations of Myers et al. on patients with myocardial infarction.

Whether one believes that the excitation wave passes from within outward through the entire wall of the left ventricle or only in the subepicardial layers of this chamber, the actual direction of the wave with respect to the surface of the ventricle is of considerable interest This is true because, if the direction of excitation is parallel to the lead field of a precordial lead, the voltages developed within the ventricle will produce a maximum deflection in the tracing obtained; whereas, if there is a considerable angle between the direction of excitation and that of the lead field, the same voltages will produce a much smaller deflection in the tracing In Fig 4-30C the pathway of excitation through the left ventricle is assumed to be a purely radial spread with the wave of excitation passing through the wall in a direction that is normal to the endocardial and epicardial surfaces of the chamber. How closely this figure represents the true situation in the human heart is unknown but, with normal intraventricular conduction, it may not be greatly in error. If the lead fields of the anterior chest lead and lead V_6 (shown in Fig. 4-29, parts C and E) are correlated with the pathways of excitation (shown in Fig 4-30C) the genesis of the QRS complexes in the leads mentioned is pretty clear

In some electrocardiograms, particularly

is closer to the left ventricle. If one remembers that the lead fields for the anterior chest lead and lead V_6 must remain relatively constant, irrespective of the presence or absence of left bundle branch block, it is hard to escape the conclusion that, with this conduction defect, there must be a change in the direction of excitation in the free wall of the left ventricle. If the path of excitation were in an oblique direction through much of the anterior and lateral wall of the left ventricle (Fig. 4-30D), the correspondence between the lead fields of the anterior chest lead and lead V_6 (Fig. 4-29, parts D and E) and the direction of excitation would explain both the large S waves in the former and the small R waves in lead V_6

INTRACAVITARY LEADS

Electrocardiograms traced with an electrode inside the ventricles have been taken in experimental animals for many years, more recently, with the development of techniques for intracardiac catheterization, many intracavitary electrocardiograms have been recorded in human subjects. The majority of the latter have been taken with the electrode in the right side of the heart, but a fair number have also been obtained from the left atrium or ventricle Leads of this kind are obviously not practical for ordinary diagnostic work, but they have been helpful in confirming some theoretical ideas concerning the pathways of excitation in the ventricles and also in explaining some peculiarities seen in precordial leads

Keeping in mind the discussion of excitation in the ventricles given earlier in this section and referring to Fig 4-30C, one might expect that the cavities of both ventricles would be negative throughout the activation of these chambers except for a short period of initial positivity in the right ventricle due to early excitation of the left side of the septum. These statements, of course, assume the presence of normal intraventricular conduction and have been amply confirmed by intracavitary tracings in man. When right bundle branch block exists, there is usually initial positivity of greater magnitude and duration in the cavity of the right ventricle than is seen with normal intraventricular conduction, and the cavity of the left ventricle is negative throughout ventricular excitation. The latter fact explains why changes in the QRS complex, due to myocardial infarction, are preserved when right bundle branch block is present. With left bundle branch block, on the other hand, the cavity of the left ventricle is initially positive, and this is the reason why QRS findings, due to infarction, are usually absent under these circumstances. With left bundle branch block, the cavity of the right ventricle is usually negative during the entire period of ventricular activation.

[illegible]

large R waves in chest lead V_1 It has been generally assumed that the R wave is caused largely by the excitation wave passing toward the electrode through the thick right ventricle, but the Q waves are more difficult to explain. Sodi Pallares and associates have made extensive studies with intracavitary leads, both in experimental animals and in man Among many other contributions, they have shown that tracings taken with an electrode inside the right atrium in patients with right ventricular hypertrophy often strongly resemble tracings of chest lead V_1 recorded from the same individuals, i.e., the QRS complexes are of the qR type, referred to above. For this reason, these investigators suggest that the complexes in question, in lead V_1, are right atrial potentials

areas inscribed under these multiphasic T waves would be potentially more informative if placed in a more quantitatively exact positive or negative position.

It will be noted, as previously described, that, except for occasional rare instances, positive T waves in leads from the right side of the precordium are normally observed only during the first 24 hr of postnatal life. From this chart can also be observed the farthest lead to the left of the precordium in which inverted or multiphasic T waves may be expected to occur in the different age groups. It might be added that a more accurate means of representing these data would probably be to convert them into measurements of total T-wave area instead of just direction and amplitude, and then to express these areas as related to that of the QRS portion of the same ventricular complex.

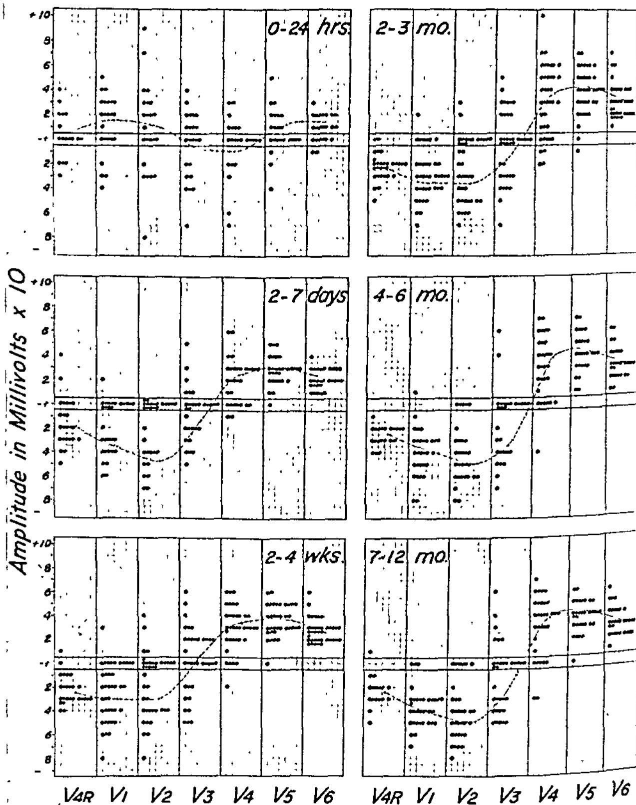


Fig. 4-32. Actual measurements for the direction and amplitude of the precordial lead T waves in 200 normal infants from birth to 1 year of age The interrupted line represents average measurements. The dotted area represents the incidence of multiphasic deflections which were not used for calculating the average in each group It should be noted that the measurement of actual

that are present at the site of the first precordial lead as a result of the hypertrophy and the clockwise rotation of the heart so commonly present in patients with marked enlargement of the right ventricle.

In the interpretation of *intracavitary electrocardiograms*, it must be remembered that the catheter technique inevitably makes these leads different from all others, since the exact location of the exploring electrode may be uncertain It is usually possible to identify the cavity of the heart in which the electrode lies, but its distance from the endocardium and its relation to important structures within the heart, when a tracing is taken, are usually unknown. Furthermore, the electrode often shifts its position from moment to moment, due to the motior [illegible] tween ele[illegible] gram even more [illegible] contact with or is very close to the endocardium, the lead is essentially a direct one, and its lead field will be greatly concentrated in the closely adjacent muscle This, of course, accentuates the influence of this nearby muscle as compared with more remote parts of the heart and may lead to the inscription of tracings that are difficult to interpret with certainty. This situation is most likely to arise if the electrode is close to the septum near some of the special conducting pathways in this structure

ELECTROCARDIOGRAPHY IN NORMAL INFANTS AND CHILDREN

The electrocardiogram provides two basic types of information about (1) the origin and transmission of the electrical impulse responsible for the heartbeat, and (2) the sequence of ventricular de- and repolarization which is responsible for the form of the ventricular deflections The latter may be modified by a number of factors including *ventricular work (pressure and volume flow) and therefore size,* which constitutes one of the most important clinical applications of electrocardiography in infants and children

The complete sequence of ventricular activation may be studied in its spatial projection; or according to the concept of the unipolar lead electrocardiogram, individual deflections in multiple semidirect (precordial) leads may be analyzed and interpreted in terms of more or less specific, or at least predominant, *cardiac chamber activity*. In the latter category, some of the simple measurements which are of greatest importance with relation to right and left ventricular size are the positive amplitude and inscription time of the RS wave and the direction and amplitude of the T wave in those precordial leads which predominantly represent right and left epicardial potential variations Normal measurements for the initial ventricular deflections (QRS) are given as averages in Fig. 4-31. Normal T-wave measurements are given, both as averages and as total distribution, in Fig. 4-32. Representative electrocardiographic patterns during *the normal neonatal period* are illustrated in Fig 4-33. More complete statistical analyses of these and other measurements are available in the literature.

It would appear, from a comparison of these normal data with those derived from infants and children with various types of heart disease, that, with certain qualifications, one can interpret these electrocardiographic measurements with considerable accuracy in terms of relative right and left ventricular size. In the case of the precordial lead T-wave pattern, one can further gain reasonably accurate information regarding right and perhaps also left ventricular pressure relationships The electrocardiogram thus provides (1) *information regarding heart size*, which cannot be gained as accurately by any other clinical or conventional radiographic techniques, and (2) information regarding *cardiac function*, only obtainable otherwise by direct heart catheterization

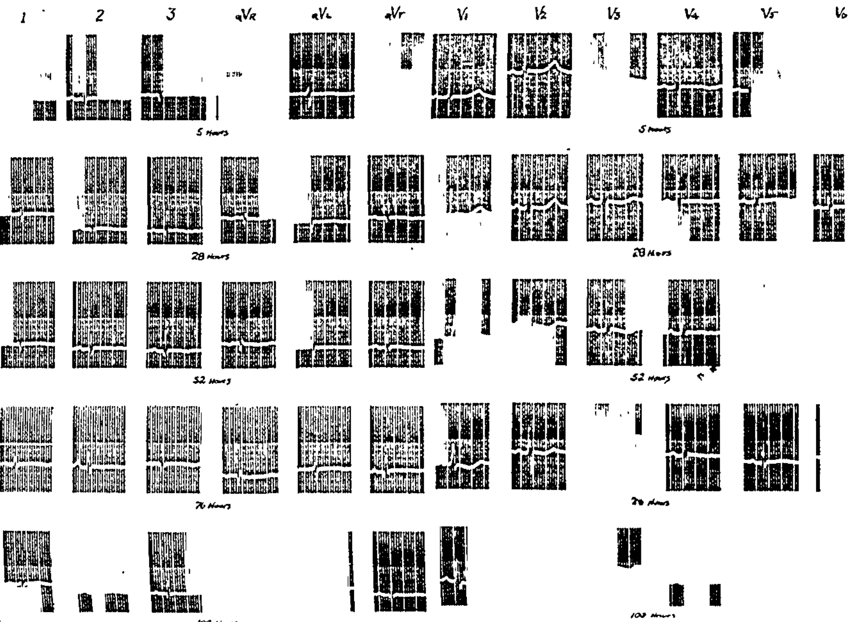


Fig. 4-33. Representative electrocardiographic patterns in a normal infant during the first 4 days of life. In the precordial leads note the progression of the T waves from positive to negative in leads from the right side of the precordium and the reverse pattern in leads from the left side of the precordium.

TABLE 4-2. SUMMARY OF QRS ABNORMALITIES

A. Normal

QRS duration 0.08–0.09, normal axis; narrow angle between initial and terminal vectors



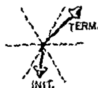
B. Myocardial infarction

1. Uncomplicated: Normal QRS duration; initial *vector points away* from infarcted region of left ventricle; terminal vector normal

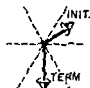


2. Peri-infarction block: Wide *angle* between initial and terminal vectors, QRS duration 0.08–0.10

a. Anterolateral: Initial vector *points inferiorly;* LAD *of* terminal vector



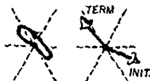
b. Diaphragmatic: Initial vector points leftward; terminal vector points inferiorly



C. Conduction defects

1. Without QRS prolongation

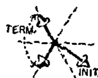
a. $S_1S_2S_3$: Initial vector *normally directed;* terminal vector points rightward, superiorly *and anteriorly* (R' at V-1)



b. Left ventricular parietal block: *Initial vector* normally directed, *marked* LAD of terminal vector

2. With QRS prolongation

a. Uncomplicated RBBB: *QRS 0.10* sec or more, *initial* vector normally directed, terminal *vector* points rightward and anteriorly



b. RBBB with infarction. *Same* as above except *initial* vector has infarct direction

2

Vectorcardiography

Interpretation of the Clinical Electrocardiogram by Vector Methods

ROBERT P. GRANT

Spatial Vectorcardiography

ARTHUR GRISHMAN

INTERPRETATION OF THE CLINICAL ELECTROCARDIOGRAM BY VECTOR METHODS

There are two different methods for using vector analytic principles in clinical electrocardiography In the first, four electrodes placed on the body surface and a cathode-tube oscilloscope are used to define what are believed to be the resultant electrical forces actually generated within the heart This is the approach which has been most widely used during the past decade, and several monographs on its applications have been published However, this approach so far has been of little clinical use.

The other application of vector methods has been less widely used but promises to be much more useful clinically In this method, the vector is used simply as a means for putting together or integrating into a single measurement the information contained in the various leads of the clinical tracing In this approach, *the vector* is simply a graph, similar to other graphs used in medicine, such as the temperature chart or the glucose tolerance curve, which relate a number of independent observations of a given process to one another in order to give a single, over-all quantitative view of the process In fact, much of the progress that has been made in diagnostic medicine in the past 50 years is related to the development of methods for quantitatively graphing physiological processes, and the electrical properties of the heart should be no exception.

Most graphs used in medicine are two-dimensional plots of magnitude against time. As used in clinical electrocardiography, the *vector is a three-dimensional plot*, which is an unfamiliar graph for most physicians, and perhaps that is why electrocardiographers and vectorcardiographers have been slow to recognize its usefulness in this form *It is a graph plotting magnitude with reference to the three dimensions of space* Yet its general properties are the same as for any other graph. For example, just as one can predict the level of blood glucose at any instant from the glucose tolerance curve, so one can predict the contour of the electrocardiographic deflection which might be recorded at any region of the body from the vectors plotted from the conventional clinical tracing. This is one of the more powerful aspects of vectorelectrocardiography for it makes the clinician master of QRS and T deflections no matter in what lead or where on the body they are recorded.

In using the vector in this way, it is not necessary to assume that it has any certain relationship to the electrical forces actually generated by the heart. The vector is simply that force which, if generated at the center of a volume conductor resembling the body, would produce the deflections which were encountered in the clinical tracing. This is an important point because it means that it is not necessary to make any assumptions regarding the internal electrical properties of the body

all presently known QRS-complex abnormalities. From the directions of the vectors it is possible to define the diagnostic *alterations in* the contour of the QRS complex in any lead no matter where on the body surface it may be obtained for each syndrome and its variants This table then contains information which is the equivalent of many hundreds of actual tracings

METHODS

In order to understand the way in which vector methods can be used in interpreting the clinical tracing one must understand the way in which the deflection is a measurement of an electrical force It is now generally accepted that, as far as body surface leads are concerned, *at each instant during the heart cycle there can be considered to be a sin*[illegible] *the heart* [illegible] from it. [illegible] the heart [illegible] body surface is the same as that which takes place in a volume conductor when there is a single electrical force generated at its center (Fig. 4-34A). When a single central electrical force is generated, *one-half* of the body surface is a region of *electrical positivity* and, if a V lead were placed there, it would record a positive deflection The other half is a region of *electrical negativity* and a V lead placed here would record an inverted deflection The particular distribution of positivity and negativity on the chest is a function of the direction of the vector at that instant. The area of positivity is separated from the area of negativity by a narrow pathway around the chest which possesses zero potential; an electrode placed here would record *no* deflection. Thus zone is called the *null* or *transitional pathway*, and the simplest way to visualize it is as the pathway of intersection around the chest of the plane perpendicular to the vector at its origin (Fig. 4-34B).

When the distribution of potential on the body surface is seen in this way, it becomes apparent that the leads of the clinical tracing are simply so many "samples" of body-surface potential at a few arbitrarily spaced points on the chest surface. This brings up another analogy with the glucose tolerance test, for, in this test too, several samples are obtained at arbitrarily spaced intervals during a complicated biochemical process However, obtaining the samples is only the beginning of the glucose tolerance test Next, the amount of glucose

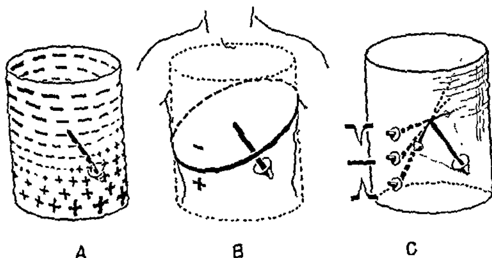
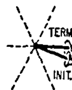


Fig 4-34. *Distribution of electrical potential on the chest from the vector point of view.* A A single *electrical force is shown being generated at the center of a cylindrical volume conductor. Electrical positivity is found on the region toward which the vector is pointing; negativity is found on the region from which the vector is pointing* B The areas of positivity and negativity are separated by a pathway of zero potential. This pathway defines a plane perpendicular to the vector at its origin *These same principles determine the distribution of potential on the surface of the chest for a given vector* C. *Three V-lead electrodes* are shown placed on the surface of the volume conductor. The dotted lines are the axes for the three leads. The deflection measures the projection of the vector on the axis *for each lead. It can be seen that the middle electrode has an axis perpendicular to the vector and therefore writes no deflection* This electrode lies on *the null pathway for the vector shown in (B). (From Grant Clinical Electrocardiography: The Spatial Vector Approach,* McGraw-Hill–Blakiston, 1957.)

TABLE 4-2. SUMMARY OF QRS ABNORMALITIES (*Cont.*)

c. LBBB: QRS 0.12 sec or more; normal axis; narrow angle between initial and terminal vectors; infarction does not alter this



d Peri-infarction block with QRS prolongation: Same directions of initial and terminal vectors as in conventional peri-infarction block, terminal vector prolonged so that QRS duration is 0.12 sec or more

e. Quinidine prolongation: May produce BBB or may simply prolong both initial and terminal components without altering looping contour

D Ventricular hypertrophy

1. LVH. Increased magnitude of mean QRS vector, normal axis; narrow angle between initial and terminal vector; occasionally complicated by parietal block

2 RVH. Any of three patterns—(1) RAD, (2) initial vector anteriorly directed (R at V-1 more than 0.04 sec), (3) terminal vector rightward and anteriorly directed (R' at V-1, often with $S_1S_2S_3$)

or the heart, and there is no question whatever regarding the validity of the method—which is not at all the case for the cathode-tube method of vectorcardiography

Another important attribute of this method for studying the clinical tracing is that it converts the information contained in the various leads into its proper physical "units." The deflections are, after all, simply graphic measurements of the impact of electrical forces on the galvanometer Therefore the most rational method for interpreting the tracing would be to convert its information into the form of *directed electrical forces or vectors* In this sense, the vector is to electrocardiography what the milligram or the milliequivalent is to biochemistry.

It is not meant that vector methods should supplant the more familiar "pattern" methods of interpretation, but rather that they should supplement them. When, for example, a tracing has the classical "pattern" of acute myocardial infarction it is no more necessary to study it in terms of vectors than it is necessary for ordinary clinical purposes to obtain an accurate measurement of body temperature when the patient has an obvious raging fever. On the other hand, the vector method is the only one which will explain why a particular lead has a certain type of deflection deformity in acute infarction. And when the tracing is perplexing or borderline, or when there is a slight difference in follow-up tracings the importance of which is unclear, then the vector method of studying the clinical tracing is the most objective and accurate that has so far been devised

Since the vector is simply a particular way of expressing information contained in the vari-

vector Doing this has many advantages for clinical electrocardiography. In the first place, it is more objective and quantitative than is the method based upon the "patterns" of the deflections in one or another lead. Another virtue, for the beginner at least, is the fact that it greatly simplifies the criteria for identifying the normal and abnormal tracing. Instead of having to memorize "patterns" of deflections on each of the various leads for a given electrocardiographic syndrome one need memorize the direction of only one or another vector. This is exemplified in Table 4-2. In this are described the vector characteristics of nearly

and QRS vectors.

During the QRS cycle, depolarization spreads from one region of the heart to another and therefore the direction of the QRS vector changes from instant to instant during the QRS cycle. At each instant, the vector is relatively perpendicular to the region of the heart undergoing activation. This is shown schematically in Fig. 4-36A, with numbers indicating the sequence in which the various instantaneous vectors may be generated. Of course the galvanometer "sees" these vectors as if they all arose from the same point at the center of the body. Therefore, in Fig. 4-36B, the instantaneous vectors are redrawn as if they all arose from the same point. Under these circumstances, the simplest way to indicate the change in magnitude and direction of the vector from instant to instant is to draw a line through the termini of the instantaneous vectors of Fig. 4-36B and add an arrowhead to indicate the sequence in which they are generated, this has been done in Fig. 4-36C. The figure produced is called the "QRS loop."

The QRS complex which a given lead records is simply the measurement of the projection or "shadow" of the QRS loop on the axis of that lead. This is shown in Fig. 4-36C. The first limb of the loop casts a "shadow" on lead I pointing toward the negative electrode. Therefore, the complex starts with a negative deflection (*Q wave*), the depth of which measures the size of the projection of that limb of the loop on the lead axis. The third instantaneous vector of the loop is perpendicular to the lead axis. This means that, at that instant during the writing of the loop, there is no "shadow" on the lead axis and therefore the deflection returns to the base line. The "shadow" cast by the remainder of the loop on the lead axis points toward the positive electrode, and therefore the remainder of the QRS complex is an upright deflection (*R wave*), and the amplitude of the R wave is a measurement of how large the projection of this limb of the loop is on the lead axis.

There are three different ways in which QRS vectors can be studied.

Study of the Change in Direction of the Vector from Instant to Instant During a Single QRS Cycle. This is done in the cathode-tube method of vectorcardiography, photographing the "shadow" cast by the spatial QRS loop on one or another plane of the body. However, such loops can be plotted quite as accurately, though in less detail, from the conventional clinical leads. Clinical electrocardiography has not advanced far enough to put to use the instant-to-instant changes in QRS vectors, and

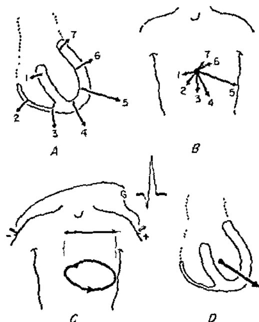


Fig. 4-36. Scheme of QRS vectors. A. Numbered vectors indicating the change in magnitude, direction, and origin of vectors from instant to instant during a single QRS cycle. B. The vectors are all drawn as if they arose from the same point at the center of the body, which is the way the galvanometer "sees" them. C. A line has been drawn through the termini of the vectors in (B), this is the frontal plane projection of the QRS loop for this patient. The heavily dotted line represents the axis for lead I. The deflection it writes is a measurement of the projection of the loop on that axis. D. The frontal plane projection of the mean QRS vector for this patient. (*From Grant. Clinical Electrocardiography: The Spatial Vector Approach. McGraw-Hill–Blakiston, 1957.*)

so far there are few clinical situations in which the QRS loop is indispensable in electrocardiographic diagnosis. For this reason, and because space is limited, the method for plotting loops from the clinical tracing will not be described.

Measurement of the Mean Spatial QRS Vector. This describes the average, or mean, direction of all instantaneous vectors of a single QRS cycle (Fig. 4-36D). It is exactly the same measurement as Einthoven's "mean electrical axis." It tends to reflect the general lay of the QRS electrical field; all so-called "electrical positions of the heart" are indicated by different directions of the mean QRS vector. Because the QRS forces of the heart are relatively more stable than the T-wave forces, the mean QRS vector is also useful as a reference item against which to compare the direction of the mean T vector in a given tracing. The angle between the mean QRS vector and the mean T vector

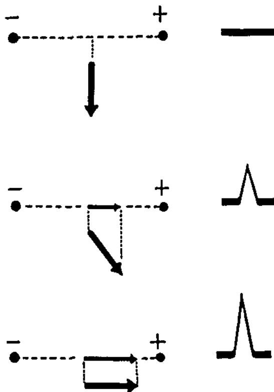


Fig. 4-35. Principle of projection as applied to the electrocardiogram The heavily dotted line represents the axis for a bipolar lead. Three different directions of the vector are shown The amplitude of the deflection written by the lead is a measurement of the size of the projection of the vector on the axis of the lead In the upper example, the vector is perpendicular to the axis and therefore no deflection is written. (*From Grant. Clinical Electrocardiography The Spatial Vector Approach. McGraw-Hill–Blakiston, 1957*)

in each sample must be weighed and the values for the several samples plotted on a graph in order to quantitate the process they are sampling The same is true of clinical electrocardiography Having obtained the "samples" (the deflections on the various leads), the quantity of electrical energy in each must be measured and then the values for each of the various leads graphed together in order to define the distribution of potential which they are sampling Only when this is done is the electrocardiogram being studied quantitatively The simplest way to do this is to plot *vectors* from the tracing, for these implicitly indicate the distribution of body surface potential

To return to the method for plotting vectors from the clinical tracing, if one knows the null pathway around the chest for any vector, the direction of that vector is known because *the vector is perpendicular to the plane defined by the null pathway.* Therefore, the most accurate way to plot the vectors would be to record deflections from all regions of the chest and find the distribution around the chest of electrode locations where zero deflections were recorded, for this will be the null pathway for that vector. As will be shown later, this method is actually used when, for one reason or another, the data of the conventional clinical tracing are inconclusive. However, it is too time-consuming for routine clinical use and the 12 leads of the conventional tracing are used instead These leads cover only a small eccentric region of the chest and there is therefore some sacrifice of accuracy.

The way in which the deflection in a given lead is a measurement of a vector involves the principle of projection (Fig. 4-35). First, consider how this takes place for bipolar leads such as *the standard limb leads.* Consider the hypothetical line joining the two electrode locations in Fig. 4-34 as the axis of the lead. The amplitude of the deflection is an accurate measurement of the size of the projection of the vector on the axis of the lead A simple way to visualize this is to consider that the projection of a vector on a lead axis would be its "shadow" cast on the lead axis if there were a light source perpendicular to the lead axis It will be noted in the figure that, when the vector is perpendicular to the axis of the lead, no projection (no "shadow") is cast on the axis. Therefore the galvanometer will show no deflection for this direction of the vector On the other hand, when the vector is parallel with the lead axis, the projection is maximal and the galvanometer will be deflected maximally under these circumstances. The same principles hold for unipolar or V leads, except that now the axis for the lead is the hypothetical line from the exploring electrode to the origin of the vector when the vector is perpendicular to the axis of a unipolar lead, the deflection is zero, on the other hand, when the vector is parallel with the axis of the lead, the deflection will be maximal in amplitude (Three such unipolar leads are shown in Fig 4-34C.) The deflection is *positive* or upright when the projection of the vector points *toward* the positive electrode of the lead (which, for unipolar leads, is the exploring electrode) and is *negative* or inverted when the projection points *away* from the positive electrode (i.e., toward the negative electrode for a bipolar lead) This principle of projection explains why there is a distribution of zero deflections around the chest for a given vector: when a V lead is recorded from a point on the null pathway, its lead axis is perpendicular to the vector, as shown by the middle electrode in Fig. 4-34C, under these circumstances, it records a zero deflection

Space does not permit a detailed description of the method for plotting vectors from the clinical tracing, the insights it gives, and the sources of error which occur Since the later discussion of

the clinical applications of the method will be concerned with certain QRS-vector syndromes, the method will be described only for QRS complexes and QRS vectors.

During the QRS *cycle*, depolarization spreads from one region of the heart to another and therefore the direction of the QRS vector changes from instant to instant during the QRS cycle. At each instant, the vector is relatively perpendicular to the region of the heart undergoing activation. Thus is shown schematically in Fig. 4-36A, with numbers indicating the sequence in which the various instantaneous vectors may be generated. Of course the galvanometer "sees" these vectors as if they all arose from the same point at the center of the body. Therefore, in Fig. 4-36B, the instantaneous vectors are redrawn as if they all arose from the same point. Under these circumstances, the simplest way to indicate the change in magnitude and direction of the vector from instant to instant is to draw a line through the termini of the instantaneous vectors of Fig 4-36B and add an arrowhead to indicate the sequence in which they are generated, thus has been done in Fig. 4-36C. The figure produced is called the "QRS loop."

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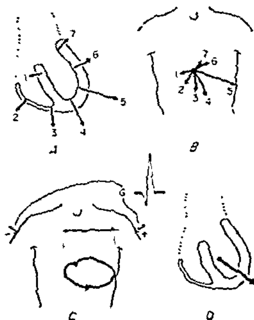


Fig 4-36. Scheme of QRS vectors. A. Numbered vectors indicating the change in magnitude, direction, and origin of vectors from instant to instant during a single QRS cycle. B. The vectors are all drawn as if they arose from the same point at the center of the body, which is the way the galvanometer "sees" them. C. A line has been drawn through the termini of the vectors in (B), this is the frontal plane projection of the QRS loop for this patient. The heavily dotted line represents the axis for lead I. The deflection it writes is a measurement of the projection of the loop on that axis. D. The frontal plane projection of the mean QRS vector for this patient. (From Grant. *Clinical Electrocardiography. The Spatial Vector Approach*. McGraw-Hill-Blakiston, 1957.)

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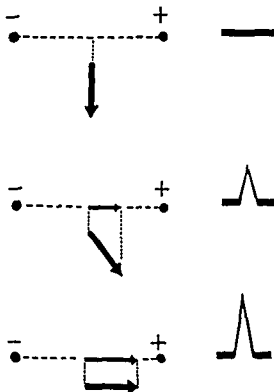


Fig. 4-35. Principle of projection as applied to the electrocardiogram The heavily dotted line represents the axis for a bipolar lead. Three different directions of the vector are shown The amplitude of the deflection written by the lead is a measurement of the size of the projection of the vector on the axis of the lead In the upper example, the vector is perpendicular to the axis and therefore no deflection is written (*From Grant Clinical Electrocardiography The Spatial Vector Approach. McGraw-Hill–Blakiston, 1957.*)

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The way in which the deflection in a given lead is a measurement of a vector involves the principle of projection (Fig. 4-35). First, consider how this takes place for bipolar leads such as *the standard limb leads.* Consider the hypothetical line joining the two electrode locations in Fig. 4-34 as the axis of the lead. The amplitude of the deflection is an accurate measurement of the size of the projection of the vector on the axis of the lead. A simple way to visualize this is to consider that the projection of a vector on a lead axis would be its "shadow" cast on the lead axis if there were a light source perpendicular to the lead axis. It will be noted in the figure that, when the vector is perpendicular to the axis of the lead, no projection (no "shadow") is cast on the axis. Therefore the galvanometer will show no deflection for this direction of the vector On the other hand, when the vector is parallel with the lead axis, the projection is maximal and the galvanometer will be deflected maximally under these circumstances. The same principles hold for unipolar or V leads, except that now the axis for the lead is the hypothetical line from the exploring electrode to the origin of the vector when the vector is perpendicular to the axis of a unipolar lead, the deflection is zero, on the other hand, when the vector is parallel with the axis of the lead, the deflection will be maximal in amplitude (Three such unipolar leads are shown in Fig 4-34C) The deflection is *positive* or upright when the projection of the vector points *toward* the positive electrode of the lead (which, for unipolar leads, is the exploring electrode) and is *negative* or inverted when the projection points *away* from the positive electrode (i e, toward the negative electrode for a bipolar lead) This principle of projection explains why there is a distribution of zero deflections around the chest for a given vector. when a V lead is recorded from a point on the null pathway, its lead axis is perpendicular to the vector, as shown by the middle electrode in Fig. 4-34C, under these circumstances, it records a zero deflection

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vector in the frontal plane of the body by ... ing the limb lead deflections. This gives the projection or "shadow" of the spatial vector on the frontal plane of the body. Next one determines how far anteriad or posteriad from the frontal plane projection the spatial vector is directed, and this is done from the precordial leads.

To plot the frontal plane direction of a vector from the limb leads one must be familiar with the triaxial reference figure, the method of its construction, and the polarity of its axes. As already discussed (Chap 1, Classic Electrocardiography), it consists of the axes for the three standard limb leads drawn in their proper directions as recorded in the body but shifted for the purposes of the graph so that they all pass through the same zero point in the electrical field. To have all the coordinates of the graph pass through the zero point of the graph is a convention used in nearly all types of graphs. The direction of the vector is determined by applying the principles of projection illustrated in Fig. 4-35. If the net enclosed area under the QRS complex on one of the standard limb leads is zero (as much area under its positive components as under its negative components) the mean QRS vector must be perpendicular to the axis for that lead; if, on the other hand, the net enclosed area of the QRS complex is conspicuously greatest in one of the three leads, the mean QRS vector must be parallel with the axis for that lead (Fig 4-37A).

To determine the extent to which the spatial vector is directed anteriad or posteriad from the direction of the frontal plane, the null pathway for the vector is plotted. To do this, first draw a line perpendicular to the frontal plane vector at

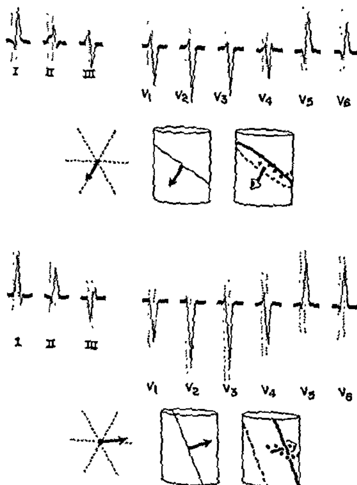


Fig. 4-38 Method for plotting the initial 0.04-sec vector. The first 0.04 sec of each QRS complex is demarcated by the two vertical dotted lines. Two cases are shown. Exactly the same principles are used as in Fig. 4-37. (From Grant, Clinical Electrocardiography: The Spatial Vector Approach, McGraw-Hill-Blakiston, 1957.)

is the most sensitive and accurate method so far devised for evaluating the T waves in the electrocardiogram.

Division of QRS Interval. The most useful method for studying QRS-complex abnormalities is *division of the QRS interval in half and the separate plotting of a mean vector for the first and last 0.04 sec of the QRS interval, the "initial 0.04-sec vector" and the "terminal 0.04-sec vector."* This is rational because the initial and terminal QRS vectors are generated from different regions of the heart (the initial 0.04-sec vector is generated primarily from the endocardial layers of the ventricles while the terminal 0.04-sec vector is generated primarily from epicardial layers) and are differently affected by various diseases. For example, *myocardial infarction has an altogether different effect on initial vectors than on terminal vectors, hypertrophy affects terminal but not initial vectors, etc.*

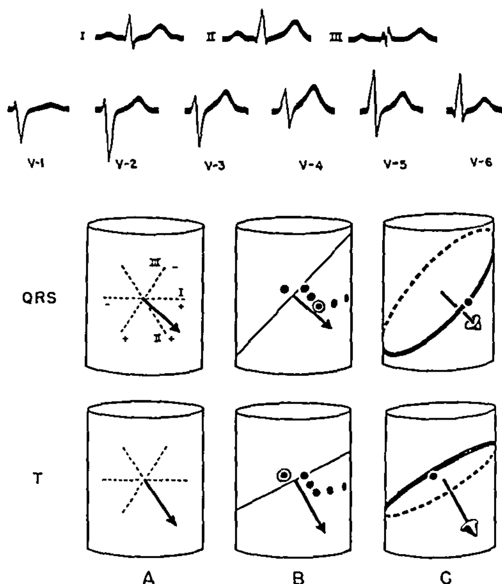


Fig. 4-37. Method for plotting the mean spatial QRS and T vectors. A. The frontal plane projection of the mean vectors is calculated from the limb lead deflections on the triaxial reference figure. The net enclosed area of the QRS complex is smallest on lead III but is not zero, therefore, the mean QRS vector is nearly perpendicular to the lead III axis. The net enclosed area of the T wave is largest in lead II; therefore, the mean T vector is parallel with the lead II axis, pointing toward the positive electrode of the lead because the deflection is positive on this lead. B. The frontal plane direction of the vector is plotted in the cylindrical reference figure. A line is drawn perpendicular to each vector at its origin; this line will be a diameter of the null plane. C. The precordial lead of which the net enclosed area is most nearly zero is identified; an ellipse is drawn symmetrically around the diameter to pass through this electrode position. (From Grant. *Clinical Electrocardiography: The Spatial Vector Approach.* McGraw-Hill–Blakiston, 1957.)

There are two steps in plotting vectors from the clinical tracing. First, one plots *the direction* of the vector *in* the frontal plane of *the body by studying the* limb lead deflections. This gives the projection or "shadow" of the spatial vector on the frontal plane of the body. Next one determines *how far* anteriad or posteriad from the frontal plane projection the spatial vector is directed, and this is done from the precordial leads.

To plot the frontal plane direction of a vector from the limb leads one must be familiar with the triaxial reference figure, the method of its construction, and the polarity of its axes. As already discussed (Chap. 1, Classic Electrocardiography), it consists of the axes for the three standard limb leads drawn in their proper directions as recorded in the body but shifted for the purposes of the graph so that they all pass through the same zero point *in the* electrical field. To have all the coordinates of the graph pass through the zero point of the graph is a convention used *in nearly all types of graphs*. *The direction of the vector is* determined by applying the principles of projection illustrated in Fig. 4-35. If the net enclosed area under the QRS complex on one of the standard limb leads is zero (as much area *under its* positive components as under its negative components) the mean QRS vector must be perpendicular to the axis for that lead, if, on the other hand, the net enclosed area of the *QRS* complex is conspicuously greatest in one of *the three leads*, the mean QRS vector must be parallel with the axis for that lead (Fig. 4-37A).

To determine the extent to which the spatial vector is directed anteriad or posteriad from the direction of the frontal plane, the null pathway for the vector is plotted. To do this, first draw a line perpendicular to the frontal plane vector at

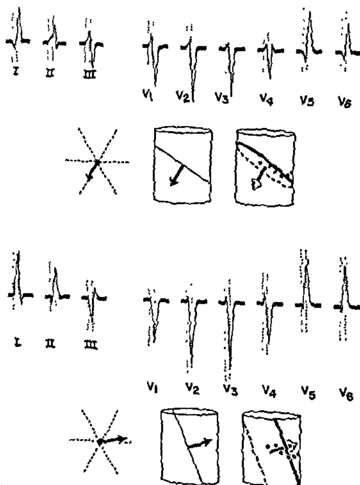


Fig. 4-38. Method for plotting the initial 0.04-sec vector The first 0.04 sec of each QRS complex is demarcated by the two vertical dotted lines. Two cases are shown. Exactly the same principles are used as in Fig. 4-37. (From Grant, *Clinical Electrocardiography: The Spatial Vector Approach,* McGraw-Hill–Blakiston, 1957.)

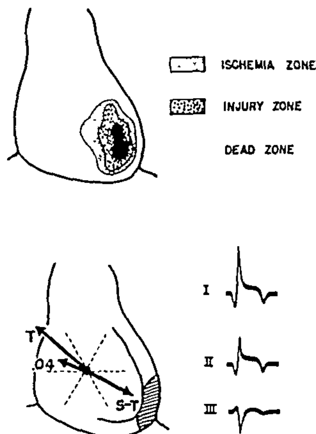


Fig. 4-39. Three vector abnormalities in acute myocardial infarction Above, the distribution of the electrical defects responsible for the electrocardiographic changes. Below, the directions certain of the vectors are caused to take by virtue of the particular location of this infarction, with the deformities they would produce in the three standard limb leads (*From Grant. Clinical Electrocardiography The Spatial Vector Approach. McGraw-Hill–Blakiston, 1957*)

its origin (Fig 4-37B) This line will be a diameter of the plane defined by the null pathway Next, identify the precordial lead which recorded the most nearly null deflection (the deflection with as much enclosed area in its positive component as in its negative component) Then draw an ellipse symmetrically around the diameter and passing through the precordial lead which recorded the null deflection (Fig. 4-37C) This ellipse defines a plane in the body, and the particular tilt of the plane indicates how far anteriad or posteriad the spatial vector is directed from its projection on the frontal plane.

The same principles are used in plotting the initial and terminal 0 04-sec spatial vectors except that here one studies the net enclosed area for just the first or the last 0 04 sec of the QRS complex in the various leads. This is the portion of the deflection enclosed by two vertical time lines in the tracing (Fig. 4-38).

APPLICATIONS

Space does not permit a review of the various P, QRS, S-T, and T syndromes from the vector point of view. However, to ilustrate the usefulness and application of the method, the vector abnormalities of myocardial infarction will be briefly discussed with particular reference to certain QRS-vector abnormalities.

In acute infarction, there are four vector abnormalities which may occur (Figs. 4-39 and 4-40).

1. *There is a deformity of the vectors during the first 0.04 sec of the QRS interval,* with the initial 0.04-sec vector tending to point *away* from the electrical location of the infarct. This is called the "dead zone effect."

2. A *displacement of the S-T segment* appears, which is due to injury current. The S-T vector tends to point *toward* the electrical location of the injury and is called the "injury effect"

3 The mean T vector is altered in direction due to *slowing of repolarization* at the infarcted region. There is little participation of T vectors from this region in forming the mean T vector, and therefore the mean spatial T vector tends to point *away* from the infarct. This is called the "ischemia effect."

4 In about fifty per cent of patients with QRS deformity of infarction, the terminal 0.04-sec vector is changed in direction, tending to point in a direction oposite to that of the initial 0 04-sec vector. This is called "peri-infarction block" The following discussion will be concerned only with initial and terminal QRS-vector abnormalities of infarction.

The alteration in the direction of the initial 0 04-sec vector accounts for the Q waves seen in the clinical tracing following infarction. The way this takes place is as follows. Depolarization spreads to the various regions of the subendocardium of the left ventricle extremely rapidly and, in effect, all regions of the endocardium contribute electrical forces simultaneously during the first 0 04 sec of the QRS interval (Fig. 4-40A). The initial 0.04-sec vector is a resultant of all these vectors; therefore, in the normal subject, it points leftward and inferiad, as shown to the right of this figure With this direction, the "shadow" cast on each of the three standard limb leads by the initial 0.04-sec vector is positive; therefore

there are normally no Q waves in these leads. Of course, when the initial 0 04-sec vector is more horizontally leftward in direction, as is often the cases in stockily built patients, it will have a negative projection on lead III, and this is the only one of the standard limb leads which may normally have an initial Q wave of 0 04-sec duration. With infarction, the infarcted region of the endocardium can no longer generate electrical forces and therefore the initial 0.04-sec vector tends to point away from the location of the infarct (Fig. 4-40B). With this direction, the initial 0 04-sec vector will have a negative projection on one or more of the standard limb leads (lead I in the case illustrated) and produce Q waves on these leads.

Any region of the left ventricle may be infarcted In Fig. 4-40C is shown a diagram of the left ventricle in the chest as viewed frontally. The left ventricle can be divided into five general topographical regions as shown in Fig. 4-40D and an infarct may lie in or between any of these regions. At the bottom of the figure are shown the directions which the initial 0 04-sec vector will take in pointing away from each, in turn, of these five regions. When one is familiar with the way in which

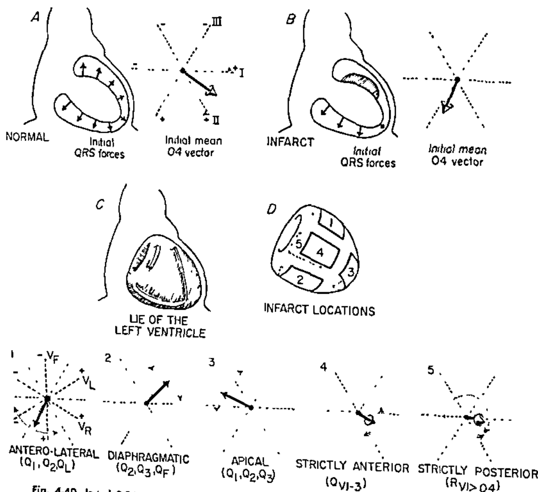


Fig. 4-40. Initial 0 04-sec vector deformity of infarction In (C), which shows the lie of the left ventricle as viewed frontally, the free wall of the right ventricle has been removed at its line of attachment to the left ventricle Note that the septum is parallel with the frontal plane of the body and that the right ventricle lies anteriorly to the left ventricle The polarity of the triaxial figure for the three standard limb leads is shown in (A). In vector diagram 1, a hexaxial reference figure is shown, combining the axes for the standard and the unipolar limb leads. The polarity of the unipolar limb leads is indicated. (*From Grant. Circulation.* Grune & Stratton, 1956.)

spatial vectors project positive and negative deflections on the axes for the various leads of the clinical tracing, he can tell from a glance at the vector diagram which leads will show initial Q waves and which will not for each of these five initial 0.04-sec vector directions. For those not yet conversant with how this is done, the distribution of Q waves in the conventional leads for each infarct location is cited below the vector diagrams, with the topographical name which has become widely accepted for each of these five regions. Here then, in five vector diagrams, is implicit the distribution of Q waves for all possible locations of infarction and for all possible leads—the entire lexicon of infarction "Q waves." This is another illustration of the way in which vector methods simplify criteria for electrocardiographic interpretation.

There are several important aspects of the deformity of the QRS complex in infarction which these five diagrams illustrate In the first place, since all body surface leads are recording from the same vectors, if the initial 0.04-sec vector is abnormal in direction, the initial part of the QRS complex must be abnormal in all body surface leads, and not only in those leads which have Q waves For example, in *anterolateral infarction* (vector diagram 1 in Fig. 4-40), the initial 0.04-sec vector may project a negative deflection (Q waves) on leads I and VL However, its projection on the other limb leads is also abnormal For example, leads III and VR will usually have initial R waves, and such R waves in these leads are just as abnormal as the Q waves in leads I and VL. The recognition of abnormal Q waves in certain leads has for many years been the basis for the "pattern" diagnosis of infarction, but it must not be overlooked that the initial part of the QRS complex in the other leads will be just as abnormal.

For another example, in strictly *posterior infarction*, the initial 0.04-sec vector is directed markedly anteriorly (vector diagram 5 of Fig. 4-40). Since the area of electrical negativity for a vector is the region of the chest *away* from which the vector points, it follows that in this type of infarction there will be Q waves of 0.04-sec duration on the back of the chest However, none of the leads of the conventional clinical tracing are recorded from this region of the chest. Here then is a type of infarction which may have *no* Q waves in any of the leads of the conventional tracing. Nevertheless, because the initial 0.04-sec vector is abnormal in direction, the initial part of the QRS complex must be deformed in the various leads With the initial 0.04-sec vector pointing anteriorly, there will be an initial R wave at V_1 and V_2 lasting 0.04 sec or more. This is not seen normally in older subjects, and these broad initial R waves, manifestations of the abnormally directed initial 0.04-sec vector, are just as diagnostic of infarction as the Q waves on the back.

The body surface is divided into an area of electrical positivity and an area of electrical negativity by every vector (Fig. 4-34A). This is as true of the initial 0.04-sec vector as for any other. It means that, in every subject, normal or abnormal, there must be one area of the chest where V leads will record initial *R waves* of 0.04-sec duration, and another region of the chest where *Q waves* of 0.04-sec duration will be recorded. It is not commonly realized that every subject has a region of the chest where such Q waves can be recorded. Indeed, it has often been recommended, in cases of suspected infarction with no diagnostic Q waves in the conventional leads, that additional leads be taken exploring other regions of the chest to "pick up" the Q waves. This is a dangerous practice unless it is realized that in every subject, normal and abnormal, Q waves indistinguishable from those of infarction are recorded if one explores far enough The only difference between the Q waves of the normal subject and the Q waves in the patient with infarction is the region of the body where the Q waves are recorded. Since, with infarction, the initial 0.04-sec vector points away from the location of the infarct, a basic criterion for the diagnosis of infarction depends upon whether the initial 0.04-sec vector has such a direction that it might be pointing away from a region of the left ventricle

Of course, *the initial 0.04-sec vector is the mean of all instantaneous vectors during the first 0.04 sec of the QRS interval*, and these vectors may not all have the same direction. Q waves of 0.04-sec duration will be recorded only in the region which is negative throughout the initial 0.04 sec of the QRS interval. In Fig 4-41, null pathways are shown for three instants during the first 0.04 sec of the QRS

interval, the region of the chest which is negative throughout the first 0.04 sec is determined by superimposing the null pathways for all three instants, as shown below (same figure). This is called the "Q area."

It is a common clinical opinion that, in a case of infarction, the more leads there are with Q waves the more severe the infarct. However, from these considerations of the Q area, it can be seen that the number of leads that record Q waves depends upon the location of the Q area relative to the location of the leads; and the location of the Q area depends upon the location of the infarct and not on its severity. Furthermore, the number of leads which record Q waves depends upon the size of the Q area and this is determined by the extent to which there is a difference in direction of instantaneous vectors during the first 0.04 sec of the QRS interval. If there is little difference in their direction, the Q area will be large and may include nearly half of the chest surface. Under these circumstances, the probability is high that one or more leads of the conventional tracing will lie in the Q area On the other hand, if the initial instantaneous vectors are markedly different in direction, the Q area will be quite small and possibly none, or only one, of the precordial leads will lie in it In Fig 4-41 for example, precordial leads V_1 to V_3 lie in the Q area and record Q waves, the Q area also includes the left shoulder and therefore lead VL also records a Q wave of 0 04-sec duration The factors which govern the directions of instantaneous QRS vectors during the first 0.04 sec in infarction are not known, but there is no evidence that the clinical severity of infarction is one of them.

The most precise method so far devised for studying the initial QRS deformity of infarction is to plot the Q area for the given patient from multiple V leads recorded in a systematic pattern from all regions of the chest. This is even more accurate than the cathode tube method for recording vectors, and is the only remaining approach that may be made in a patient with borderline Q waves and an inconclusive direction of the initial 0 04-sec vector. To decide whether the Q area has a normal or abnormal location in a given patient, one must visualize (in the given patient) a plane passing through the AV orifices of the left ventricle. For most subjects, this plane will intersect the body surface in a more or less sagittal fashion passing to the left of the spine posteriorly, across the left clavicle, and descending down the front of the chest slightly to the right of the sternum. According to present knowledge, when the Q area is primarily to the right of this plane, the initial QRS forces are within normal limits; when it is primarily to the left, the initial QRS deformity of infarction is probably present.

Now one may turn to the terminal 0.04-sec vector deformity produced by infarction, the peri-infarction block. The simplest explanation of this deformity is illustrated in Fig 4-42. The infarct prevents the radial spread of exci-

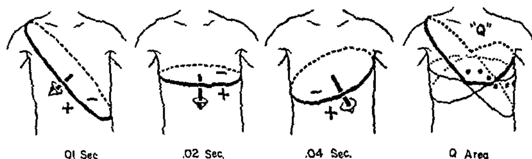


Fig. 4-41. The Q area Transitional pathways are plotted for three instants during the first 0 04 sec of the QRS interval indicating the distribution of positivity and negativity on the chest at each instant. On the right the three transitional pathways are combined, and the region of the chest which is negative throughout the first 0.04 sec is outlined by the heavy line. This is the region of the chest where Q waves of 0 04-sec duration would be recorded in this patient. The six precordial lead electrode locations are indicated by dots. (From Grant. Clinical Electrocardiography: The Spatial Vector Approach McGraw-Hill–Blakiston, 1957.)

spatial vectors project positive and negative deflections on the axes for the various leads of the clinical tracing, he can tell from a glance at the vector diagram which leads will show initial Q waves and which will not for each of these five initial 0.04-sec vector directions. For *those not yet conversant with how this is done*, the distribution of Q waves in the conventional leads for each infarct location is cited below the vector diagrams, with the topographical name which has become widely accepted for each of these five regions. Here then, in five vector diagrams, is implicit the distribution of Q waves for all possible locations of infarction and for all possible leads—the entire lexicon of infarction "Q waves." This is another illustration of the way in which vector methods simplify criteria for electrocardiographic interpretation.

There are several important aspects of the *deformity of the QRS complex in infarction* which these five diagrams illustrate. In the first place, since all body surface leads are recording from the same vectors, if the initial 0.04-sec vector is abnormal in direction, the initial part of the QRS complex must be abnormal in all body surface leads, and not only in those leads which have Q waves. For example, in *anterolateral infarction* (vector diagram 1 in Fig. 4-40), the initial 0.04-sec vector may project a negative deflection (Q waves) on leads I and VL. However, its projection on the other limb leads is also abnormal. For example, leads III and VR will usually have initial R *waves, and such R waves in these leads are* just as abnormal as the Q waves in leads I and VL. The recognition of abnormal Q waves in certain leads has for many years been the basis for the "pattern" diagnosis of infarction, but it must not be overlooked that the initial part of the QRS complex in the other leads will be just as abnormal.

For another example, in strictly *posterior infarction*, the initial 0.04-sec vector is directed markedly anteriorly (vector diagram 5 of Fig 4-40). Since the area of electrical negativity for a vector is the region of the chest *away* from which the vector points, it follows that in this type of infarction there will be Q waves of 0.04-sec duration on the back of the chest. However, none of the leads of the conventional clinical tracing are recorded from this region of the chest. Here then is a type of infarction which may have *no* Q waves in any of the leads of the conventional tracing. Nevertheless, because the initial 0.04-sec vector is abnormal in direction, the initial part of the QRS complex must be deformed in the various leads. With the initial 0.04-sec vector pointing anteriorly, there will be an initial R wave at V_1 and V_2 lasting 0.04 sec or more. This is not seen normally in older subjects, and these broad initial R waves, manifestations of the abnormally directed initial 0.04-sec vector, are just as diagnostic of infarction as the Q waves on the back.

The body surface is divided into an area of electrical positivity and an area of electrical negativity by every vector (Fig. 4-34A). This is as true of the initial 0.04-sec vector as for any other. It means that, in every subject, normal or abnormal, there must be one area of the chest where V leads will record initial *R waves* of 0.04-sec duration, and another *region of the* chest where *Q waves* of 0.04-sec duration will be recorded. It is not commonly realized that every subject has a region of the chest where such Q waves can be recorded. Indeed, it has often been recommended, in cases of suspected infarction with no diagnostic Q waves in the conventional leads, that additional leads be taken exploring other regions of the chest to "pick up" the Q waves. This is a dangerous practice unless it is realized that in every subject, normal and abnormal, Q waves indistinguishable from those of infarction are recorded if one explores far enough. The only difference *between the Q waves of the normal* subject and the Q waves in the patient with infarction is the region of the body where the Q waves are recorded. Since, with infarction, the initial 0.04-sec vector points away from the location of the infarct, a basic criterion for the diagnosis of infarction depends upon whether the initial 0.04-sec vector has such a direction that it might be pointing away from a region of the left ventricle.

Of course, *the initial 0.04-sec vector is the mean of all instantaneous vectors during the first 0.04 sec of the QRS interval,* and these vectors may not all have the same direction. Q waves of 0.04-sec duration will be recorded only in the region which is negative throughout the initial 0.04 sec of the QRS interval. In Fig. 4-41, null pathways are shown for three instants during the first 0.04 sec of the QRS

body build, these Q and R waves might no longer be present in the conventional leads. The initial 0.04-sec/terminal 0.04-sec angle would still be diagnostically *wide, and this*, then, is a type of infarction which would be missed by current pattern criteria but would be recognized by the use of vector methods (Fig. 4-43).

In diaphragmatic peri-infarction block, the *initial 0.04-sec vector is directed* leftward and *superiad, indicating the presence of* Q waves in leads II, III and VF, the terminal vector is relatively opposite to the initial 0.04-sec vector in direction and points inferiad and slightly rightward, indicating a terminal S wave in lead I. This *means* that diaphragmatic *peri-infarction block may occasionally produce a tracing showing right axis deviation.* It is differentiated from the right axis deviation of uncomplicated right bundle branch block by the wide angle between the initial and terminal 0.04-sec vectors.

In most cases of periinfarction block there is little or no lengthening of the QRS interval. *However, occasionally* the QRS interval *may be prolonged to* 0.12, 0.14, or even 0.16 sec, a degree of lengthening that is also seen in bundle branch block. Usually this takes place some time after the acute *infarction has subsided and is perhaps* related to scarring and contraction in the region of the infarct. The last *part* of the QRS complex in each lead is *the only part* to show prolongation. when it occurs in anterolateral *peri-infarction* block, the deflections in the various *leads often resemble* left bundle branch block, when it *happens in* diaphragmatic infarction, it produces limb lead deflections which resemble right bundle branch block. *Anterolateral peri-infarction* block with prolongation can be *differentiated from left* bundle branch block by the *width of the angle* between the initial 0.04-sec vector and the mean vector for the remainder of the QRS complex. Thus angle rarely exceeds 45° in left bundle branch block *while, in peri-infarction* block, as *has been mentioned, it usually* exceeds *100°*. Furthermore, *the terminal* vector in anterolateral peri-infarction block may be directed sufficiently anteriad to produce a terminal R′ deflection at V_2, a phenomenon which never occurs in left bundle branch block.

The angle *between the initial 0.04-sec vector* and the terminal *0.04-sec* vector cannot be used to differentiate diaphragmatic peri-infarction block with prolongation from right bundle branch block. The reason for this is that, in

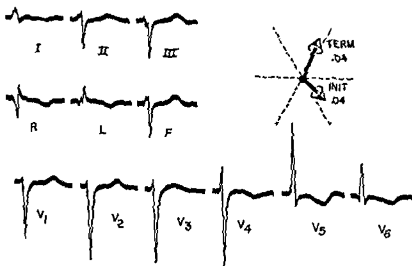


Fig. 4-43. Anterolateral peri-infarction block. The initial and *terminal* 0.04-sec vectors are shown plotted from the conventional leads. The angle between the *initial and terminal* 0.04-sec vectors *(plotted) is diagnostically wide.* However, because the entire QRS *electrical field* is rotated somewhat *counterclockwise, the initial* 0.04-sec vector does not *have a direction* which will project *significantly broad* Q waves on any *of the conventional leads, and one would* not be able to *make the diagnosis* of infarction in this case from the patterns *of the conventional leads.* (From Grant. *Clinical Electrocardiography. The Spatial Vector Approach.* McGraw-Hill–Blakiston, 1957.)

tation to the epicardium overlying the infarct and this then is the last region to be depolarized. The terminal 0.04-sec vector is dominated by these vectors and determines the last half of the QRS complex in all leads. Thus, the initial 0.04-sec vector and the terminal 0.04-sec vector are more or less opposite to each other in direction and the wide angle between the initial and terminal 0.04-sec vectors is the basic criterion for the diagnosis of periinfarction block. However, peri-infarction block is seen primarily accompanying only two of the five possible locations of infarction, either diaphragmatic or anterolateral infarction. It is rarely seen with other electrical locations of infarction and, when it is, the terminal 0.04-sec vector tends to have the direction seen in either the anterolateral or the diaphragmatic infarction For this reason, an alternative explanation has been offered for peri-infarction block, based upon the fact that the left bundle branch divides into two groups of fibers early in its course. One division spreads superiad, and an infarct in its distribution would cause excitation to spread from below upward, accounting for the leftward terminal 0.04-sec vector in anterolateral peri-infarction block (Fig. 4-39). The other division of the left bundle extends inferiad, and an infarct in its distribution would cause excitation to spread from above downward. As a result, the terminal 0.04-sec vector would point inferiad and slightly rightward, and this is what is seen in diaphragmatic peri-infarction block.

The terminal 0.04-sec vector in *anterolateral peri-infarction block* is markedly leftward in direction. Thus, anterolateral peri-infarction block is an important cause of left axis deviation. However, it can be readily differentiated from left axis deviation of other causations by measuring the angle between the initial and terminal 0.04-sec vectors. In uncomplicated left axis deviation, this angle is usually less than 60°, while in anterolateral peri-infarction block it usually exceeds 100°. From a pattern point of view, this means that, if in a tracing with marked left axis deviation (more than −30° on the triaxial reference figure), there is a Q wave in leads I and VL lasting 0.03 to 0.04 sec and an initial R wave in lead III lasting more than 0.04 sec, anterolateral peri-infarction block is probably present. However, it may be necessary to measure the angle between the initial and terminal 0.04-sec vectors to be confident of the diagnosis. On the other hand, if there were a slight counterclockwise rotation of the entire QRS electrical field, as might happen due to certain changes in heart position or

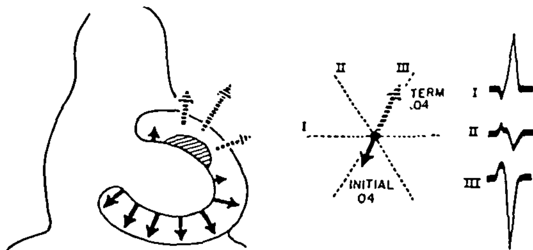


Fig. 4-42. Peri-infarction block Initial vectors are indicated by solid arrows; terminal vectors are indicated by the lined arrows There is no electrical activity during the first 0 04 sec in the region of the infarct and, as a result, the initial 0.04-sec vector points away from the site of the infarct The last region of the heart to be depolarized is the region overlying the infarct, therefore the terminal 0.04-sec vector is dominated by vectors from this region. As a result the initial and terminal 0 04-sec vectors are nearly opposite to one another in direction. In this particular case, they would write deflections in the standard limb leads as shown on the right. This is the type of change that is seen with anterolateral peri-infarction block. Note the marked left axis deviation that has been produced. (*From Grant. Circulation. Grune & Stratton, 1956.*)

essentially regarded as characteristic for the specific area.

These assumptions were based upon animal experiments in which thoracic electrocardiograms had configurations identical with those obtained from the myocardial surface subjacent to it. The former, therefore, have often been referred to as semidirect leads because of their similarity to the latter, the direct leads Although the facts established by the experiments cannot be denied, other explanations can be offered for them under changing concepts and added experience Thus, under the concept of *exploring electrocardiography*, the location of patterns regarded as characteristic for certain anatomical areas was searched for on the chest wall, extremities, intravascular (large thoracic vessels) areas, ventricular cavities, and esophagus The only limiting factor to this type of investigation is the accessibility of the area to exploration by an electrode Changing concepts tend to minimize the importance of the contributions made by specific "local potentials" since it is believed that they are not available to instrumental analysis with any of the electrocardiographic techniques presently employed.

The "vector concept" underlying spatial vectorcardiography assumes that the generation of electromotive forces by ALL *segments of the active heart contribute to one electromotive field* All electrocardiographic leads, irrespective of the technique employed, merely "tap" this field through projection upon lead lines the angle of which is determined by the respective points at which they are connected to the galvanometers It can be readily seen that the unitarian character of this *vector concept* tries to treat all electrocardiographic curves obtained from the same individual as direct derivations of one source common to all of them. The return to one of Einthoven's theories is apparent the electrical forces generated by the heart can be represented as a *dipole* at the center of a sphere with essentially homogeneous conductivity.

Although the concept of the local potential with inherent assignment of local shape specificity to the curves obtained is no longer considered valid, the enormous quantity of clinical material (with autopsy correlation) accumulated lends itself to interpretation in spite of changing concepts

THE CARDIAC DIPOLE AND VECTOR

The fundamental theoretical basis of spatial vectorcardiography is "the dipole theory," proposed by Einthoven, and further developed through experimental and theoretical review by Craib and Canfield, Wilson et al, Burger and van Milaan, Cabrera, Gillard et al, Schmitt et al, and Milnor and Talbot. The basic tenet of the dipole theory states that the electrical field generated by cardiac activity behaves as though it were produced by a simple battery with positive and negative poles close together, a battery which is immersed in a homogeneous volume conductor of body tissues and fluids. The positive and negative poles constitute a dipole and are actually formed in the body by the relationship of the positively and negatively charged ions of tissue fluid electrolytes. The manner in which forces are generated by the stimulated muscle cell, and through which the dipole relationship between ions is created and maintained, is not relevant to a discussion on spatial vectorcardiography which will be limited to the validity of the dipole concept, its properties and its recording (instrumental analysis).

An excited cardiac muscle area will assume a *negative charge* in relation to a resting one, which, therefore, becomes relatively positive. Thus, through the apposition of a negative and positive pole in close proximity to one another, a "dipole" is created. In a manner similar to the creation of a magnetic field through the North-South orientation of a magnet, the newly created dipole creates *an electrical field* around itself A line drawn through the two poles of the dipole constitutes *the dipole axis.* The direction of this line, determined by the spatial orientation of its two poles to each other, indicates the direction of positive and negative electricity in the field and, hence, the direction of the current flow. The dipole center is the point of *zero potential* between the two components of the dipole The dipole axis is more familiarly known as the electrical axis of the heart, so named by Einthoven, Fahr, and de Waart The magnitude of the dipole charge at the time of observation (*dipole moment*) is shown by using a linear measurement, specified by standardization, to express the voltage generated Transformation of voltage into a displacement of a specified magnitude allows the graphic presentation of voltage (1 cm displacement may represent 1 mv). When recorded on a kymograph or a recorder running at a known speed, the voltage is recorded with its time of occurrence correlated with other cardiac events.

The appearance of a dipole creates an electromotive force; having the properties of magnitude, direction, and sense, it is a *vector*

right bundle branch block the initial 0.04-sec vector is not affected by the block; therefore, with the initial 0.04-sec vector pointing leftward and inferiad and the terminal vector pointing anteriad and rightward, the angle between the two vectors is normally very wide. However, there is another feature which helps to differentiate them Since the right ventricle lies anteriorly to the left ventricle, *the terminal vector in right bundle branch block always points anteriad*, producing a terminal R' deflection at V_1 and V_2. On the other hand, *in diaphragmatic peri-infarction block with prolongation*, the terminal vector is generated from the diaphragmatic surface of the left ventricle; therefore, *it points inferiad and slightly posteriad*, indicating a terminal S wave in V_1 and V_2.

Space has permitted a discussion of the application of vector methods to only certain aspects of the deformity of the QRS complex in myocardial infarction. It is hoped that this discussion may demonstrate that vector methods have an important contribution to make to clinical electrocardiography. However, the use of vector methods in the study of the problems of conventional clinical electrocardiography is in its infancy. Perhaps this brief résumé will stimulate others to participate in what may bring at long last truly objective and rational criteria for the interpretation of the clinical electrocardiogram.

SPATIAL VECTORCARDIOGRAPHY

Advances in the theory and application of electrocardiography have been extensive and continue to be so, since Waller's first successful recording of the electric currents generated during the contraction of the human heart. The era of clinical electrocardiography was initiated through Einthoven's epochal contribution of designing a string galvanometer of great fidelity, making the recording of cardiac action potentials meaningful to theoretical and experimental analysis. The technical advances in apparatus design have been truly enormous with the advent of portable lightweight instruments and others with an amplification range up to 25 cm/mv.

The application of the three bipolar extremity leads has formed the basis of clinical and experimental investigations for more than two decades Little has been added since to man's knowledge of the rhythmical properties of the heart and its disturbances What Lewis had done for the analysis of the arrhythmias, Wilson similarly accomplished for the ventricular complex of the electrocardiogram. His important contributions through an analysis of precordial potentials in clinical cases and elucidation by appropriate animal experimentation, through the introduction of the "central terminal" for precordial and extremity electrocardiography, brought man to an era of intensive accumulation and study of case records and painstakingly collected autopsy correlations

No cardiac examination or evaluation is complete without an electrocardiographic study The diagnostic yield of clinical electrocardiography is great but, with the ever increasing desire to narrow the margin in order to make more and more reliable diagnoses, one continues to search for more different or improved technical approaches Here particularly, new avenues of approach, although previously pointed out and theoretically discussed, are being exploited technically to evaluate their usefulness in narrowing the diagnostic gap. Myocardial infarctions of certain localizations, for instance, seem to have defied identification until newer concepts made a new analysis possible, for example "posterior wall" infarction as distinct from "diaphragmatic." In other instances, differentiation of patterns of intraventricular conduction defects and bundle branch block from those of ventricular hypertrophy or even from those due to myocardial infarction may prove difficult or impossible. Attempts to seek additional information by means of exploring electrodes in unconventional positions were not contributory. Esophageal, intrabronchial, and multiple thoracic leads (in nonstandard positions) have been used thus The test of time, the limited clinical information gained, the inconvenience and often discomfort to the patient, have assigned to them a historical position. "Electrocardiography as a method of examination has been thoroughly explored, and it is unlikely that its usefulness will be extended to any important degree" This statement of Wolff et al finds the author in full agreement.

Exploring multiple-lead electrocardiography was originally based largely upon the concept of local potential characteristics, assuming that predominantly the potentials of the area subjacent to the exploring electrode were being recorded The different anatomical areas of the ventricular myocardium were assumed under this concept to produce electrocardiographic patterns which were

of the muscle area subjacent to the exploring electrode. The limitations of the techniques employed were apparent to Lewis, Meakins, and White (1914), becoming, however, less emphasized in subsequent years The experiments and publications of Harris and, somewhat later, of Schaefer, based on "micro" bipolar systems with the two electrode points as close to each other as possible, had drawn attention to the fallacious assumption that exact knowledge as to the spread of the excitation wave was available from experiments with semidirect or unipolar electrode systems. The most illuminating studies of Durrer, Scher, and Sodi Pallares, have begun to reestablish the foundations of knowledge about the sequence of excitation Nevertheless, years will pass before these fascinating, newly obtained facts will penetrate to the teaching level of clinical electrocardiography.

The heart can be considered to be a spherical shell with a septum dividing it into two chambers. The stimulus appears to reach the muscle fibers of the anterosuperior segment of the septum first. The balance of forces at this time is oriented so that the vector of the septal balance of forces is directed anteriad and to the right Thereafter, many segments of the septum and ventricular walls are stimulated simultaneously. Then, only the sum or net balance of all forces generated at any time is available to instrumental analysis applicable in humans

HISTORICAL DEVELOPMENT

The spatial cardiac vector, inscribed by all instantaneous cardiac vectors, is believed to contain all the information as to the field strength—and thereby the balance of forces—of the emf created through cardiac activity.

Sufficient information about the normal instantaneous progressive balance of forces is available to ascribe deviations from the normal range to specific changes of the contributing muscle elements. Abnormal sequences of stimulation can be identified with equal facility

A brief presentation of the historical development of vectorcardiography and its techniques may facilitate a discussion of the dipole theory underlying it.

Einthoven, Fahr, and de Waart (1913) published an account of the determination of the resultant manifest potential as based upon the scheme of the equilateral triangle, the vertices of which are represented by the right arm, left arm, and left leg electrodes. By this technique, the net amplitude and direction of the QRS complex in each of the three standard extremity leads were plotted along the side of the triangle. The magnitude and direction of the resultant manifest potential differences were then determined geometrically by the use of polar coordinates. The resultant manifest potential difference was thus represented as a single vector. the magnitude, direction, and sense of the total emfs of the heart as projected to the plane formed by the three leads. The authors also determined the values, i e, the angles and the magnitude of the manifest resultant emf for several instances during cardiac activation. Although not following their computation through to the point of geometric presentation, their data were of such completeness as to allow this to be done decades later (Wolff et al) Einthoven and Fahr thus observed that homogeneous peaks of the QRS complex in the three leads did not occur in phase, i e., peaks of the R waves did not occur simultaneously. Williams was the first to summate the synchronously occurring potentials of the extremity leads to one single curve which he termed the *vector diagram* He concluded that the difference in phase of homogeneous peaks of the QRS complex depicted the vectorial character of the potential changes in the heart Although discussing the spread of the excitation wave, Fahr (1920) gave an account of vector interpretation of the electrocardiogram with emphasis on the phase relationship of the potentials of the three extremity leads. He also postulated that the criteria prevalent at that time for the diagnosis of right and left bundle branch block were incorrect and suggested criteria which are presently regarded as correct.

Whereas Williams plotted the vector diagram on a polar coordinate system, Mann adapted this technique of vectorial reconstruction to a rectangular coordinate system, determining the value of the horizontal axis from lead I and for the vertical axis geometrically from leads II and III $[(L_2 + L_3)/3]$. Little use was made of the time-consuming technique, however, since each case required careful construction of the three matched or simultaneously recorded electrocardiograms which formed the basis for the analysis. At present it is only of historical interest. In subsequent years, Mann developed a special three-pole galvanometer in searching for instrumental means for combining the three standard leads into one single curve. A detailed description of his ingenious apparatus followed (1938).

Advances in design of cathode-ray tubes with

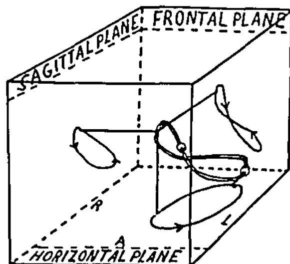


Fig. 4-44. The spatial cardiac vector is located at the center of the cube (which in turn represents eight equidistant points on a sphere). It should be visualized as having been drawn by the arrow tips of innumerable instantaneous vectors It is graphically represented through the projection to three preselected planes. the horizontal, frontal, and sagittal.

quantity. In contradistinction to so-called scalar quantities such as mass, volume, and potential difference, which have no reference to direction, vector quantities are subject to the mathematical rules governing vector addition and can be visualized through vector presentation.

The mathematical symbol which represents a vector quantity is an arrow. The direction of the arrow indicates the direction of the emf created by a dipole in space, the length of the arrow indicates the magnitude of the force; and the head of the arrow points in the direction of the positive field, thereby following the choice of polarity of Einthoven Vector presentation, therefore, in a single symbol can express the three properties of a dipole, namely, magnitude, direction, and sense (polarity)

At every instant of cardiac activity myriads of minute or "elementary" dipoles arise, each of which develops an "elementary" emf which can be represented by an "elementary" vector Each elementary dipole contributes to the magnitude, direction, and sense of the total or resultant emf at the instant of observation, which might be referred to as the balance of forces. Therefore, at any one instant, one dipole (the resultant of all elementary dipoles) and one vector (the resultant of all elementary vectors) can be applied to represent the characteristics of the cardiac electromotive field force within the body. The resultant vector is termed the *instantaneous cardiac vector.* The geometric structure inscribed by the (imaginary) arrowheads of all instantaneous cardiac vectors during an entire cycle of cardiac activity is termed *the cardiac vector.*

The heart and its active muscle segments have a three-dimensional arrangement. The instantaneous vectors representing the magnitude, direction, and sense (polarity) of the electromotive field forces of each movement correspondingly have a three-dimensional or spatial orientation, i.e., left or right, superior or inferior, anterior or posterior. A spatial cardiac vector loop is inscribed by the terminal points of all instantaneous vectors throughout one cardiac cycle (Fig. 4-44). The loop inscribed by atrial activity is termed the P loop; that produced by depolarization of the ventricular muscle mass, the QRS loop; and the one inscribed by the repolarization process, the T loop. From the cardiac vector loop, one can derive information concerning the balance of forces contributed by the muscle aspects at any one time.

THE SPREAD OF THE EXCITATION WAVE

The sequence of excitation of the ventricular musculature and the generation of emf which follows the excitation are determined by the anatomy of the bundle of His and the Purkinje fibers.

The study of galvanometric deflections from leads at or near the heart can yield only general information as to the order of the spread of the excitation wave since these are merely recording points in the field of the resultant dipole (Fahr). Better understanding of the various lead systems (unipolar, semiunipolar, distant electrodes paired with exploring electrode, etc) upon which such information was based makes one doubt the exactitude which was thought to be contained in the experimentally obtained data. Present knowledge of the physical properties of the lead systems most commonly employed in such experiments in the past obliges one to concur with Fahr's statement (1920) that the information is general, devoid of the exactitude implied. The curves obtained "tapped the spatial cardiac vector," i e , the resultant of all forces generated, not predominantly the electrical events

of the muscle area subjacent to the exploring electrode. The limitations of the techniques employed were apparent to Lewis, Meakins, and White (1914), becoming, however, less emphasized in subsequent years. The experiments and publications of Harris and, somewhat later, of Schaefer, based on "micro" bipolar systems with the two electrode points as close to each other as possible, had drawn attention to the fallacious assumption that exact knowledge as to the spread of the excitation wave was available from experiments with semidirect or unipolar electrode systems The most illuminating studies of Durrer, Scher, and Sodi Pallares, have begun to reestablish the foundations of knowledge about the sequence of excitation Nevertheless, years will pass before these fascinating, newly obtained facts will penetrate to the teaching level of clinical electrocardiography.

The heart can be considered to be a spherical shell with a septum dividing it into two chambers. The stimulus appears to reach the muscle fibers of the anterosuperior segment of the septum first The balance of forces at this time is oriented so that the vector of the septal balance of forces is directed anteriad and to the right. Thereafter, many segments of the septum and ventricular walls are stimulated simultaneously Then, only the sum or net balance of all forces generated at any time is available to instrumental analysis applicable in humans.

HISTORICAL DEVELOPMENT

The spatial cardiac vector, inscribed by all instantaneous cardiac vectors, is believed to contain all the information as to the field strength—and thereby the balance of forces—of the emf created through cardiac activity

Sufficient information about the normal instantaneous progressive balance of forces is available to ascribe deviations from the normal range to specific changes of the contributing muscle elements Abnormal sequences of stimulation can be identified with equal facility.

A brief presentation of the historical development of vectorcardiography and its techniques may facilitate a discussion of the dipole theory underlying it

Einthoven, Fahr, and de Waart (1913) published an account of the determination of the resultant manifest potential as based upon the scheme of the equilateral triangle, the vertices of which are represented by the right arm, left arm, and left leg electrodes. By this technique, the net amplitude and direction of the QRS complex in each of the three standard extremity leads were plotted along the side of the triangle. The magnitude and direction of the resultant manifest potential differences were then determined geometrically by the use of polar coordinates. The resultant manifest potential difference was thus represented as a single vector: the magnitude, direction, and sense of the total emfs of the heart as projected to the plane formed by the three leads. The authors also determined the values, i.e., the angles and the magnitude of the manifest resultant emf for several instances during cardiac activation Although not following their computation through to the point of geometric presentation, their data were of such completeness as to allow this to be done decades later (Wolff et al.) Einthoven and Fahr thus observed that homogeneous peaks of the QRS complex in the three leads did not occur in phase, i.e., peaks of the R waves did not occur simultaneously. Williams was the first to summate the synchronously occurring potentials of the extremity leads to one single curve which he termed the vector diagram. He concluded that the difference in phase of homogeneous peaks of the QRS complex depicted the vec- [illegible]

[illegible] interpretation of the electrocardiogram with emphasis on the phase relationship of the potentials of the three extremity leads He also postulated that the criteria prevalent at that time for the diagnosis of right and left bundle branch block were incorrect and suggested criteria which are presently regarded as correct.

Whereas Williams plotted the vector diagram on a polar coordinate system, Mann adapted this technique of vectorial reconstruction to a rectangular coordinate system, determining the value of the horizontal axis from lead I and for the vertical axis geometrically from leads II and III $[(L_2 + L_3)/3]$. Little use was made of the time-consuming technique, however, since each case required careful construction of the three matched or simultaneously recorded electrocardiograms which formed the basis for the analysis. At present it is only of historical interest. In subsequent years, Mann developed a special three-pole galvanometer in searching for instrumental means for combining the three standard leads into one single curve A detailed description of his ingenious apparatus followed (1938).

Advances in design of cathode-ray tubes with

conventional deflection plate positions (right angles) obviated the further search for instruments of special design. They were successfully applied by Schellong, Sulzer and Duchosal, and Wilson and Johnston.

Attempts to record the spatial characteristics of the cardiac vector loop through its projection to other planes than the frontal alone have been made by Schellong, Duchosal, and Sulzer; Rochet and Vastesaeger; Cronwich, Conway, and Burch; and, more recently, by Donzelot et al; Lamb and Dimond, Burger, and Frank and Helm.

TECHNIQUE

Provided that the theoretical premise for treating the electrical field generated by the heart as a dipole is correct, there is one spatial cardiac vector which contains all information about balance of forces generated and the sequence at which they are released. This cardiac vector can be recorded with absolute accuracy with any sensible technique advocated, provided that one corrects or can correct for errors inherent within them and the biological substrate subjected to the analysis, namely, the body and the nonhomogeneous conducting properties of its tissues, within which the electromotive field exists

Electrode Placement for Spatial Vectorcardiography. Since the cardiac vector is three-dimensional, its recording requires it to be viewed as a projection to two or more preselected planes or to be made suitable for stereoptical viewing This may be likened to an architect's lot a perspective drawing will attract the eye and imagination of the prospective purchaser of a home The same sketch, although impressive to the eye and imagination, will prove useless to the contractor who requires exact dimensions Drawings showing the house projected to planes with a simple geometric relationship to each other (at 90° angle) will serve his purposes, i.e, a floor plan (transverse or horizontal plane), a side view (sagittal plane), and a front view (frontal plane projection), since they contain exact dimensions

There are several systems of electrode placement in use at present However, only two seem to be used by a large number of investigators (1) the one based on an extension of the equilateral triangle of Einthoven as proposed by Wilson, Johnston, and Kossman and applied by Conway, Cronwich, and Burch, and (2) the orthogonal system of Schellong, its modification by Duchosal and Sulzer, and its subsequent modification to the cube system electrode placement.

In the technique used by Cronwich, Conway, and Burch (based on the geometric system suggested by Wilson et al.), the equilateral triangle of Einthoven is considered to be representing the frontal plane, and a unipolar electrode located somewhere on the back is considered the summit of an equilateral tetrahedron. The placement of the back electrode is such that it records the sagittal extent of the emf.

Since the standard extremity and the unipolar extremity leads are components of the Einthoven triangle, the frontal plane projection of the vector loop recorded by this technique correlates exactly with conventionally obtained extremity leads. However, it is not altogether valid to represent the forces recorded by the extremity bipolar leads in the form of an equilateral triangle or to regard them as determining the frontal plane. The original proponents of the Einthoven triangle regarded it as only an approximation. Burger and van Milaan and Wilson and Bryant have shown that the triangle determined by the three extremities is *not* equilateral because of a marked discrepancy of the electrical properties between source and electrode of the left arm and left leg, resistance and distance being the main factors responsible for this variability. It is also doubtful that these electrodes represent a plane which is parallel to the frontal plane. The plane determined by the three electrodes may deviate by as much as 35° from the true frontal, through clockwise or counterclockwise rotation around a perpendicular axis The effects of such a tilt may be negligible for the frontal plane projection, mostly resulting in a perspective distortion of the graph If used, however, as the basis of the more complex geometric system (equilateral tetrahedron), the distortion may become too great for the graph to remain meaningful A further difficulty in the equilateral tetrahedron system is the location of the summit of the tetrahedron for the proper location of the unipolar lead VB or back electrode A slight shift in the position of this electrode, up or down, right or left, may result in complete reversal of the direction of rotation of the vector loop because of an altered position of the vector loop within the field of polarity of the lead. The incorporation of so-called unipolar leads into any system for the recording of the cardiac vector will make it particularly vulnerable to grossly inaccurate representations of the cardiac vector. Since the direction of any unipolar lead depends upon the position of the exploring electrode in relation to the dipole center (as a result of producing a so-called central terminal) and the latter's position is unknown unless specifically determined by complex methods, the angle of the sagittal unipolar lead varies considerably in normal subjects, more markedly in subjects with abnormal hearts, and

tha ... ble degree. The distance of the ... where specifically determined.

Orthogonal Arrangement. Schellong (1938) was the first to suggest abandonment of the equilateral triangle for the recording of the cardiac vector. He placed the electrodes directly on the thorax and in an orthogonal arrangement. The center of the x,y,z axes of his bipolar leads was leftward, anteriad and superiad, thus close to the dipole center.

Duchosal and Sulzer modified Schellong's technique and also utilized three bipolar leads placing them most distant to the dipole center, their axes forming the adjoining three edges of an orthogonal body the vertical axis of which was twice the length of the sagittal and horizontal axes.

The Cube Arrangement. The unequal quantitative projection of the cardiac voltages onto the bipolar leads, due to inequality of the internal angles, was (Fig. 4-45) corrected for the "cube" form of representation developed by the author.

On the basis of exacting experiments, Gillard, Hendricks, and Taccardi concluded that the electrodes are regarded as ideally placed when they are situated at the same distance from the heart, the distance between each pair is the same, and the distance between heart and electrode is about five times the heart's radius.

If one assumes that the electrical center of the heart is at the center of a sphere, eight selected points on th ... cube, each ... "E." The line from ... determine equal internal angles. The electrodes of three bipolar leads are applied to the thorax so as to form the three adjoining edges of a cube (Fig. 4-45). There are three bipolar leads: A = horizontal; B = sagittal, and C = vertical. They receive and record the cardiac voltages as projected to the interelectrode line. Two such lines

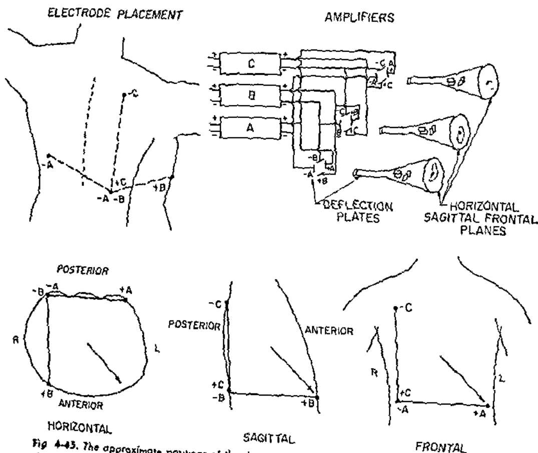


Fig. 4-45. The approximate positions of the three vector component leads, A, B, and C, and their electrode placement are shown on the left. After suitable amplification, the voltages of the three bipolar leads are connected to the deflection plates of cathode-ray oscilloscopes for either simultaneous or consecutive recording. (Lower) Schematic presentation of the three bipolar leads as they are composed to form the three planes of projection.

allow the construction of a plane since the angle is known (90°). Thus, three planes can be reconstructed: transverse or horizontal, sagittal, and vertical (commonly called frontal or parallel to frontal).

The "cube" is constructed around the assumed position of the dipole center. For this purpose, it is assumed to be located in the center of a sagittal plane passing just to the left of the sternum at the level of the 4th intercostal space. Actual determinations of the mean dipole center indicated that this was true in most normal and abnormal instances. The more significant deviations in severe pathological balances of forces affected the results in a quantitative but not in a qualitative way. The electrodes are placed so as to represent four of the corners of a cube (Fig. 4-45) having the dipole center "E" at its center, and to be as equidistant from it as the anatomy of the thorax permits. It should be noted that the cube is around the dipole center and not around the thorax, as interpreted by Schaeffer et al.—although the anatomic eccentricity of the heart influences indirectly the location of the dipole center, electrode placement is merely dependent on the eccentricity of the dipole center.

The three bipolar leads are utilized, after suitable amplification, to reconstruct planes and, through connections to the plates of a cathode-ray oscilloscope (Fig 4-45, Upper part), to allow the instantaneous presentation of the cardiac vector as it appears projected to that plane The electrode beam of the cathode-ray oscilloscope gives resultant deviation of the cardiac voltages as they appear in two leads placed at right angles to each other, i e, the phase relationship of these voltages is obtained instrumentally.

Accurate amplification free from interference can be readily obtained The author has been using the *Technicon Cardiograph* for this purpose with great satisfaction. Presentation of the three planes may be accomplished either simultaneously in a triple oscilloscope arrangement (superior for research work), or successively on a single cathode-ray indicator (Technicon Vectorscopes) by means of a simple switch arrangement A complete cardiac cycle is photographed Timing and automatic recording of the direction of rotation are accomplished through intensity modulation of the electron beam (400 times per second) and by impressing an asymmetric pattern (saw-tooth pattern modulation), shaping each of the dashes like an arrow (Figs 4-50; 4-52)

The *Sanborn Co.* has developed a vector unit which has been proved to perform with reliability and accuracy in the author's laboratory. The instrument, using a new principle for heating the preamplifier tubes, is remarkably free from interference, even at amplification ranges of 25 cm/mv.

The recording of the vectorcardiogram takes but 2 min in the author's laboratory. With some experience, the results can be obtained in most cases merely by viewing the screen of the scope without having to wait for the permanent record.

In cooperation with the *Technicon Corporation*, an apparatus has been developed for the automatic recording of the vectorcardiogram and electrocardiogram, simultaneously.

Cabrera and Aguilar studied the electrical field of the heart in cadavers with the aid of artificial dipoles. They compared three orthogonal vectorcardiographic lead systems. the one proposed by Duchosal and Sulzer; the author's cube system, and a "corrected" vector system based on principles which they had published earlier. They found the cube system and the "corrected" vectors superior to the orthogonal system of Duchosal and Sulzer.

From studies on three-dimensional homogeneous torso models, Frank suggested more recently "an accurate, clinically practical" system for spatial vectorcardiography. Using average network electrode systems (which in torso experiments were found most often in line with data obtained), he regards the technique and its theoretical basis as more accurate although still practical compared with others. Electrode positioning appears to be very critical, particularly as to level Its individual determination is not satisfactory when one examines the theory underlying it and it is impractical in actual application Apparently, wrong information was given by records (normal balance where right preponderance was expected from clinical diagnosis). Nevertheless, the general approach towards correcting network leads for vectorcardiography is a sound one, and further work in this direction should be pursued. The present status of clinical vectorcardiography does not require more than what current techniques can do With further development in the direction of quantitation and vector integration (*ventricular gradient*), present techniques might prove adequate; then no further complication of technique might become necessary. Should greater accuracy become desirable, direct electronic correction will be possible

Donzelot, Milovanovich, and Kaufmann have advocated a lead placement in which VF represents the vertical component, V_2 the sagittal, and V_6 the horizontal V_2 and V_6 are probably too close to the dipole center to reflect any but a distorted image of the cardiac vector. Furthermore, both are at different levels Although Jouve corrects for the latter, the proximity-caused distortion of the components remains.

THE VALIDITY OF THE DIPOLE AND VECTOR CONCEPT

Under the vector concept, the heart generating electricity is treated as a dipole source at the center of a sphere within an equivalent conducting medium. All electrocardiographic leads are regarded as recording the projection of the spatial cardiac vector onto the *lines of deviation* of the lead.

Several answers must be given before one can accept the dipole theory as a valid basis for vectorcardiography. The ideal physical situation requires a point source of electricity within a symmetrically shaped thorax of homogeneous conductivity.

Duchosal et al. gave one of the most important solutions to the problem. They showed that unipolar leads recorded along the axis of *diametrically opposed parts* of the body gave electrocardiograms which were, in configuration and timing, mirror images of each other. Jouve confirmed these observations in animal experiments. It thus appeared that Einthoven's hypothesis, that the electricity generated by the heart may be viewed as a single dipole, which he applied only to bipolar extremity leads, was equally valid for all leads, precordial and others. The voltage of any given electrocardiogram depended upon the distance of the lead electrode from the dipole source and the resistance of the intervening medium It *should* be possible, therefore, to predict the exact configuration of the electrocardiogram from the spatial vectorcardiogram Such derivations *show an astounding correlation*, provided they are recorded from points of a plane which passes through the dipole center

It is apparent that the intersection of two or more electrode axes furnishing sets of mirror-image electrocardiograms should determine the spatial position of the dipole center rather well This formed the basis of a convenient technique for localizing the dipole center, a technique which possibly made up through its simplicity for what it might be lacking in accuracy When the potential of a given unipolar lead is connected to the plates of a cathode-ray oscilloscope, that potential is neutralized by a potential of reverse polarity but of identical magnitude. The two unipolar leads which neutralize each other lie on opposite sides of the electrical center "E." The electrical center, rather than the anatomical center, was used for the "cube" placement of electrodes for vectorcardiography. Indirect evidence allows one to postulate that the dipole *center remains essentially stationary* during cardiac activity. This is probably due to a rather proportionate change of quantities contributing towards the balance of forces. In instances of left bundle branch block, with its incoordinate sequence of excitation, a shift of the dipole center might be expected. Marked disturbances of forces as they occur through myocardial infarction may become similarly effective Exact knowledge of the behavior of the dipole center appears to be important for the understanding of the cardiac electrical field The information can be obtained *experimentally with electronic* instruments, the greatest disadvantage of which is constituted by the expense and labor which their construction involves. The effect of the anatomical displacement of the heart during its contraction is equally unknown

In three publications, Schmitt, Levine, and Simonson present further evidence, on the basis of electrocardiographic mirror-pattern studies, for the validity of the dipole concept of electrocardiographic interpretation. They found excellent cancellation in normal subjects and most patients studied They regarded the infrequently found poor cancellation results largely due to technical limitations and found no evidence that it is due to interference of local patterns.

As mentioned before, scalar electrocardiograms can be derived from the spatial vectorcardiogram with good correlation. Duchosal et al. and the author with his coworkers were able to accomplish this. Duchosal thought that the differences occasionally encountered were, at times, due to the possible simultaneous existence of two electrical centers This appears, however, to be an unnecessary assumption. When correlations of unipolar chest leads with the transverse horizontal plane projection are being made, such unipolar chest leads should be recorded from the periphery of a plane passing through the dipole center. Corrections for angular or perspective projection should be taken into account when conventionally recorded chest leads are being used with a lead axis from the electrode location or "point" of

exploration to the dipole center (null point or electrical center) which may form an angle of considerable magnitude. Recognition of the limitations of exact correlation for graphs recorded with techniques based on opposed concepts will avoid critical conclusions of inaccuracy for one or the other.

The ingenious construction of a panoramic vectorcardiograph by Milnor et al. allowed them to study the problem more directly and with exactness. Essentially through the use of sine-cosine potentiometers, transformation of rectangular coordinates to polar coordinates was achieved instrumentally. Corresponding to the selected potentiometer positions, the spatial cardiac vector can be viewed from any angle desired. Combining this unit with an adding circuit, scalar electrocardiograms can be calculated as the projection of the spatial vectorcardiogram on any single axis By correcting for vertical deviations of unipolar chest leads from the horizontal plane at the level of the dipole center, it was possible to record curves calculated from the spatial vectorcardiogram identical to actually recorded unipolar chest leads in full detail.

Identical results were obtained in the author's laboratory with a simple and inexpensive apparatus, which obtained summation of the three component leads through a summing-circuit current determining the angle of derivation as the ratio of amplification or standardization of the component leads Treating component leads as lines, the ratio of their length (standardization) will determine the angle of the lead axis desired (arc tangent alpha). These can be applied to the transverse plane by using component leads A and B and injecting a vertical correction (component C) as required, in comparison with a directly recorded chest lead This may be likened to trigonometry, accomplished electronically through variations of standardization of the components used and summating them (addition or subtraction), again electronically. It seems possible to reconstruct all the minute details of the chest leads, although the "cube" component leads have been obtained as remotely as the anatomy of the thorax will allow Incidentally, this instrument proved most helpful in teaching the relationship of unipolar leads to spatial vectorcardiography

Thus, with added refinements in technique, it may be regarded as established that, for all practical purposes, all leads recorded from the surface of the body can be regarded as derivations of the spatial cardiac vector. No longer should one regard chest leads as being inadequately "remote" and, therefore, subject to "local" interference. It is well to realize that the heart, as a source of electricity, can be adequately treated as a dipole; its electromotive field can be presented through the spatial cardiac vector as it contains all the information available for instrumental analysis. All electrocardiographic leads are projections of this vector onto the lead line of derivation. All the information which can be obtained from them is contained within the cardiac vector or its recording, the spatial vectorcardiogram.

It should be emphasized that conventional electrocardiograms are usually devoid of phase relationship unless recorded simultaneously. Even then, this information, readily available in the vectorcardiogram, can be extracted only with time-consuming efforts. It cannot ordinarily be obtained by viewing the component leads, even when recorded at higher than conventional speed

THE PURPOSE OF VECTORCARDIOGRAPHY

The vectorcardiographic waves present the graphic picture of the phase relationship of voltages from electrocardiographic leads of known geometric relationship to each other (Fig 4-46) Although contained in the vector-component leads, their electrocardiographic analysis (duration, shape, voltage, slope, and time relationship of main deflections) gives the same information in many, but not all, situations

Properly selected, simultaneously recorded unipolar chest leads (with Wilson's central terminal) often allow an estimation of phase relationship along a plane approximately horizontal Vector plotting has certain limitations, particularly when time intervals of 0.01 sec become significant, or polyphasic complexes are encountered

Discussion is not needed about the simple fact that present-day electrocardiography in the hands of the experienced clinician is a diagnostic tool of great accuracy. There is also no question as to the desirability of narrowing the gap of equivocal, confusing, or erroneously

negative information given. The phase relationship, as computed through the cathode-ray oscilloscope and presented as a vector curve, has added new diagnostic or differential information not obtainable from the conventional electrocardiogram. The value of angiocardiography and cardiac catheterization, although of direct diagnostic value only in a percentage of cardiac patients, is not lessened by this. Beyond their diagnostic importance, their contribution to the understanding of cardiac physiology and pathology has been enormous. Similarly, vectorcardiography, beyond its direct diagnostic value, has provided a tool to teach electrocardiography through a unitarian concept, admitting deductive analytic processes in a field where memorization of empirically collected patterns was mostly required. Furthermore, the presentation of the vector concept, through the controversy it created, has stimulated new interest, work, and discussion about the foundations of "electrocardiology."

THE SPATIAL VECTORCARDIOGRAM

The representation of the vectorcardiogram of ventricular activation consists of a point of origin (white center) with a rapidly inscribed large loop, the QRS *loop*, and followed by a much more slowly inscribed smaller loop, the T loop, which *originates from the point of return of the* QRS loop (Fig. 4-50). *Since the* vectorcardiogram is recorded on a stationary film, the white center of the graph corresponds to the isoelectric line of the *normal* electrocardiogram, *i.e., the fixed point* at which the *electron beam* of the cathode-ray oscilloscope is *photographed during the P-R, S-T, and T-P* intervals. Normally, the QRS and T loops are almost *completely closed*, i.e., their points of origin and *return are essentially identical. A* dissociation of these *will result in an open loop.* In the scalar electrocardiogram, this is registered as a deviation of the S-T *segment*. An S-T vector, *as it* appears during ventricular

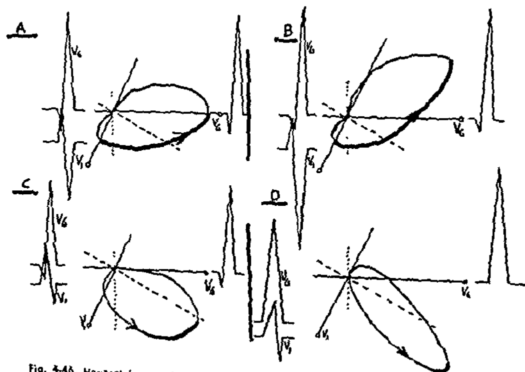


Fig. 4-46. Horizontal *vector loops shown with chest leads* V_1 *and* V_6, *simultaneously recorded* (redrawn from actual curves). The time interval between the *peak of R waves in* V_1 and V_6 *is* equivalent to the heavily drawn line of the vector loop. When less than 0.01 sec, it escapes appreciation. The vector curve is the graphic *presentation of phase relationship* of voltages of electrocardiographic leads of known geometric relationship to each other.

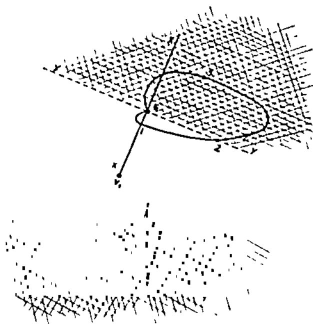


Fig. 4-47. Derivation of a unipolar lead from vector loop. The vector loop is shown to originate and return to *E*, the point of zero potential difference. A unipolar lead is obtained by drawing a line from the assumed site of an electrode (here V_1) through *E*. The segment of the vector loop proximal to *yy* will project as R waves (positive), that beyond, as S waves (negative) 1, is the peak of R, 2, is the transfer point from positive to negative; 3, is the most negative point of S.

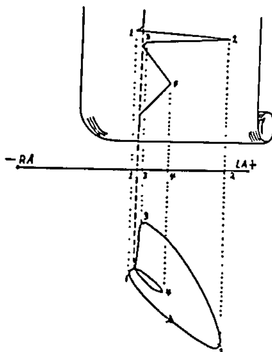


Fig. 4-48. Bipolar leads measure the potential difference betweeen the points on the body surface. Example: lead I between the right and left arm. 1, falls onto the negative field by lead I; 2, 3, fall onto the positive field; 4, represents the maximal projection of the T loop.

activation, is indicated as originating at the point of origin of the QRS loop and directed to the point of return. The direction of inscription had to be noted for each plane in the past but is now automatically recorded (Fig 4-50).

The rate and speed of inscription can be determined by comparing the distance between the interrupted segments of the vector loop Care should be taken to corroborate alteration of speed from two planes since transient, initial, or terminal slowing may be due to a perpendicular relationship of the vector loop to the plane of projection

From the spatial cardiac vector as projected to three selected planes, one can derive any of the configurations of the routine scalar electrocardiograms, unipolar as well as bipolar The justification for it and its limitations have been already discussed

THE DERIVATION OF SCALAR ELECTROCARDIOGRAPHIC LEADS

So-called unipolar leads were thought to record the potential under the exploring electrode without interference from the so-called indifferent electrode. This concept cannot be supported any longer. A "unipolar" lead system is connected on one side of the galvanometer with the electrode and on the other with the central terminal system proposed by Wilson The dipole center and the central terminal, from the electrical point of view, are identical locations within the electromotive field of the heart. Therefore, such a lead records the voltages of the cardiac vector along a lead line from the point of exploration through the dipole center *E* (Fig. 4-47). It is also referred to as *the axis of derivation* According to the adopted convention of polarity, whenever the loop is inscribed *toward* the electrode, an upward or positive deflection is recorded in the electrocardiographic record. Whenever the loop is inscribed *away* from the exploring electrode beyond *E*, a negative deflection is recorded. The amplitude of the derived complex depends upon the amplitude of the projected vector upon the lead line of derivation. Since all unipolar leads have the exploring electrode paired with the dipole center as second pole, they have the unique ability to analyze the electromotive field in a

radial fashion Therefore, their use should be regarded as the most exacting of scalar electrocardiographic techniques (provided the Wilson central terminal with the enclosed resistors is used).

Bipolar leads record the potential difference between the two electrodes derived from the spatial cardiac vector through its projection upon the interelectrode line (Fig 4-48). The positive and negative fields are divided through a perpendicular line upon the interelectrode line passing through the dipole center. In a bipolar lead, the polarity of each electrode is arbitrarily defined, with the result that designation of a deflection as positive or negative depends upon the polarity chosen.

UNIPOLAR CHEST LEADS

The configuration of a unipolar chest lead recorded at the level of the dipole center "E" can be derived with great accuracy from the horizontal or transverse plane projection of the cardiac vector (Fig. 4-49, Upper part). Although the routine *chest leads* are recorded at different levels—and mostly below "E"—the discrepancies between the derived and actually recorded leads are mostly insignificant. Adequate corrections for discrepancies can be made

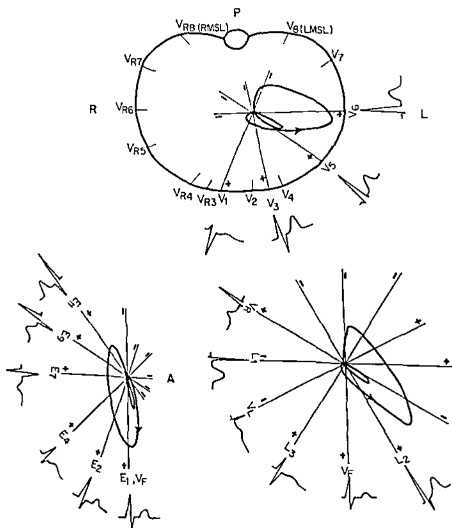


Fig. 4-49. (Upper) Schematic relationship of unipolar *chest leads* to horizontal plane projection (*R*, right, *L*, left; *P*, posterior). (Lower left) Schematic relationship of esophageal leads to sagittal plane projection, *A*, anterior. (Lower right) Frontal plane projection and its relationship to bipolar standard and unipolar extremity leads.

taking into account the distortion created by the angle of the actual line of derivation with the horizontal plane (*vertical component correction*). As discussed before, this can be accomplished electronically with astounding accuracy.

ESOPHAGEAL AND EXTREMITY LEADS

From the sagittal plane projection, *esophageal leads* (Fig 4-49, Lower left) can be derived similarly; from the frontal plane projection, the bipolar and unipolar extremity leads can be derived (Fig. 4-49, Lower right). For the latter, the triaxial system of Bayley combined with axes of the unipolar extremity leads was found to be most suitable (hexaxial system). Since often the plane of the Einthoven *triangle is found to be rotated along a vertical* axis from a true frontal by as much as 35°, lead I will not always be exactly like component lead A Under ideal conditions both should be similar to a unipolar lead V_6, provided that the angle of the line of derivation of V_6 from the horizontal plane affects its configuration only to a minor degree

With a little practice, mere inspection of the plane projections of the spatial vectorcardiogram allows prediction of the findings of routine electrocardiograms.

THE NORMAL VECTORCARDIOGRAM

Adults. The normal spatial vectorcardiogram is oriented to the left, inferiorly, and somewhat posteriorly (Fig 4-50) There is comparatively little variation found, as far as the spatial position of the vectorcardiogram in adults is concerned. The normal *QRS loop in the horizontal plane projection* is characterized by an initial small deflection anteriorly and to the right The remainder of the loop is then inscribed in a counterclockwise direction to the left and somewhat posteriorly The *initial deflection to the right* inscribes a small R wave in lead V_1 and a small Q wave in V_6 The *large deflection to the left* inscribes a prominent S wave in lead V_1 and a prominent R wave in V_6 (Fig 4-51)

The normal *QRS loop in the sagittal plane projection* is characterized by an *initial small deflection anteriorly* and occasionally *superiorly* with the remainder of the loop being inscribed *downward and somewhat posteriad* in a clockwise direction High esophageal leads are, therefore, essentially negative in configuration.

In the frontal plane, the normal *QRS loop is inscribed downward and to the left.* There may be an initial small deflection to the right, or superiad, or both. The more vertical loops in the frontal plane are inscribed in a clockwise direction; the others are inscribed in a counterclockwise direction.

In the adult, the *T loop* is usually located anteriad, inferiad, and to the right of the QRS loop, by 10 to 30°. Any marked increase in this angular deviation may prove to be an early vectorcardiographic evidence of myocardial damage, not readily available from scalar electrocardiograms.

Children. The distinguishing characteristics *of the normal routine electrocardiogram* in children are mainly attributable to the more anterior orientation of the QRS loop (Fig 4-52). As in adults, the QRS loop in the horizontal plane is inscribed in a counterclockwise direction, but the loop is oriented more anteriad and may extend an appreciable distance to the right. The precordial leads in children are thus characterized by R waves of increased amplitude and S waves of decreased amplitude over the right precordium.

The sagittal plane projection is characterized by an increased portion of the QRS loop lying anteriorly as compared to the adult. The loop *is inscribed in* a clockwise direction, as in adults At times, fairly large terminal portions of the QRS loop are inscribed superiorly and posteriorly

In *normal children,* most of the frontal plane projections of the QRS loop are inscribed in a clockwise direction Terminal portions may be found lying superiorly and to the right so that prominent R waves are found in lead VR and prominent S waves in lead I.

In *infants* within the neonatal period (up to 2 months), the vector may be oriented toward the right, resulting in occasional clockwise rotation of the QRS loop in the transverse plane projection Therefore, in this age group, in some instances, difficulties may be encountered in obtaining decisive differentiation from clockwise rotation due to right ventricular hypertrophy This is possibly caused by a persistent physiological right-ventricular preponderance.

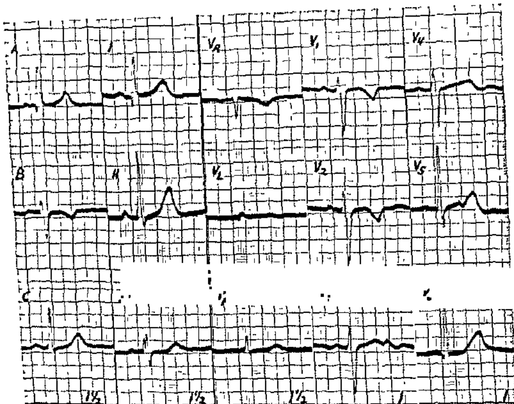


Fig. 4-50 Normal vectorcardiogram H, horizontal plane, S, sagittal plane, F, frontal plane, A, horizontal vector component lead; B, sagittal vector component lead; C, vertical vector component lead. The QRS loop in the horizontal plane (H) projection is inscribed counterclockwise, *with an essentially even spacing of the time markers (400 cgs, 0.0025 sec. apart) Its orientation* is to the left and slightly posterior. The QRS and T loops are aligned essentially along the same axis; i.e., they are essentially concordant In the sagittal plane (S), the QRS loop is inscribed clockwise and oriented inferiorly and slightly posteriorly again with essentially concordant axes for QRS *and T loops Note the initial and terminal increased proximity of time markers, its degree being* within normal variations The long axes of the QRS and T loops are concordant at about +45°. The QRS loop is inscribed counterclockwise The electrocardiogram (recorded at 5 cm/sec) relates well with the respective planes of the recorded spatial vectorcardiogram.

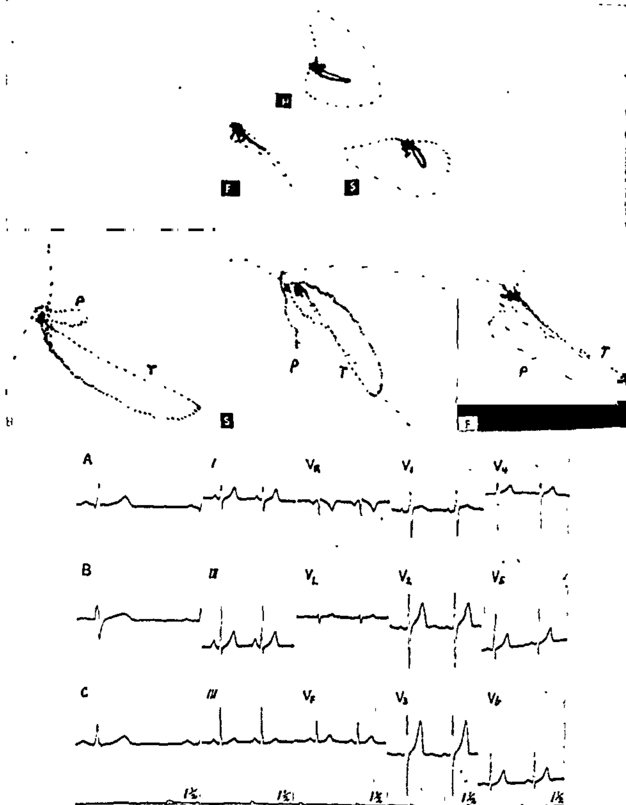


Fig. 4-51. Normal adult. Upper record shows complete *H, S,* and *F* planes of vectorcardiogram. Lower record at higher amplification (2.5 cm/mv) shows the *P* loop which is oriented to left (*H,F*) and inferiorly (*S,F*). At these high amplifications, neither the P, QRS, nor T loop is closed; i.e., a true isoelectric line only exists at slow heart rates (U-P interval). The T loop is asymmetrically inscribed, its initial half slower than the terminal one; this is a characteristic of normalcy. The electrocardiogram of the same patient is below. (A, B, and C recorded at 5 cm/sec, the other leads at 2.5 cm/sec.)

VENTRICULAR HYPERTROPHY AND BUNDLE BRANCH BLOCK

The electrocardiographic distinction between *left ventricular hypertrophy* and *left bundle branch block* is, at times, difficult when only conventional electrocardiograms are available. Conversely the spatial vectorcardiogram displays certain characteristics which permit the prompt diagnosis of conduction delay. When left ventricular hypertrophy is present, the QRS loop in the horizontal projection is characterized by an initial deflection anteriorly and somewhat to the right. The loop is then inscribed to the left and posteriorly in a counterclockwise direction The long axis of the QRS loop is more posterior than in normal persons, and there is no appreciable alteration in the distances between the time markings (Fig 4-53). The sagittal plane projection of the QRS loop is inscribed in a clockwise direction, and the loop is oriented more posteriorly than normally. The QRS loop in the frontal projection is oriented more to the left than in normal persons, and is usually inscribed in a counterclockwise direction. The T loop in each projection lies opposite the QRS loop and there is no evidence of altered proximity of the time markings. The QRS loop may fail to close prior to the inscription of the T loop, resulting

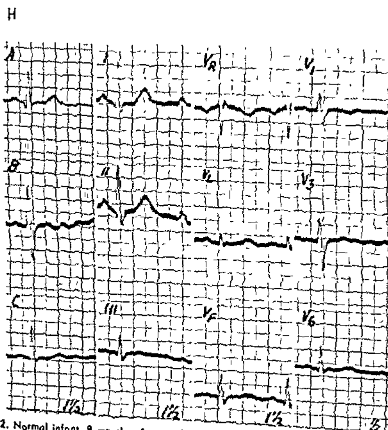


Fig. 4-52. Normal infant, 8 months of age. The vectorcardiogram has the basic characteristics of normalcy of the adult, but its initial part is oriented more anteriorly (H,S). The electrocardiogram (recorded at 5 cm/sec) correspondingly exhibits R waves of increased amplitude in V..

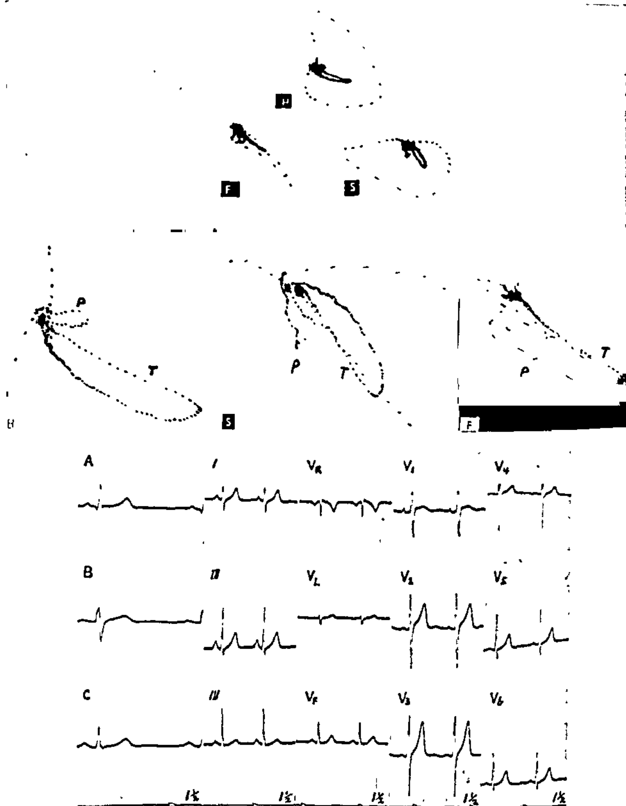
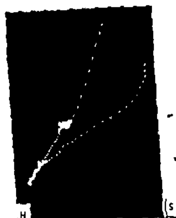
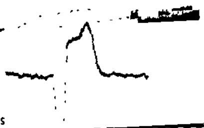


Fig. 4-51. Normal adult Upper record shows complete *H, S,* and *F* planes of vectorcardiogram. Lower record at higher amplification (2 5 cm/mv) shows the P loop which is oriented to left (*H,F*) and inferiorly (*S,F*). At these high amplifications, neither the P, QRS, nor T loop is closed; i e, a true isoelectric line only exists at slow heart rates (U-P interval). The T loop is asymmetrically inscribed, its initial half slower than the terminal one; this is a characteristic of normalcy The electrocardiogram of the same patient is below. (A, B, and C recorded at 5 cm/sec, the other leads at 2.5 cm/sec.)

A B C

H S F





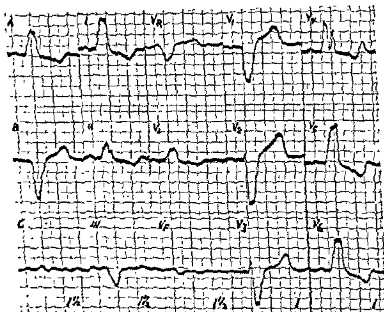


Fig. 4-54. Left bundle branch block. The vector is posteriorly and horizontally oriented, inscribed clockwise in the horizontal plane without any anterior deflection. The middle section shows a characteristic slowing of time markers. The ST vector is oriented anteriorly, to the right, and slightly superiorly with the T loop discordant with the QRS loop. The electrocardiogram (5 cm/sec) shows the corresponding changes. QS in V_1, slow plateau and upstroke in leads I, V_5, and V_6.

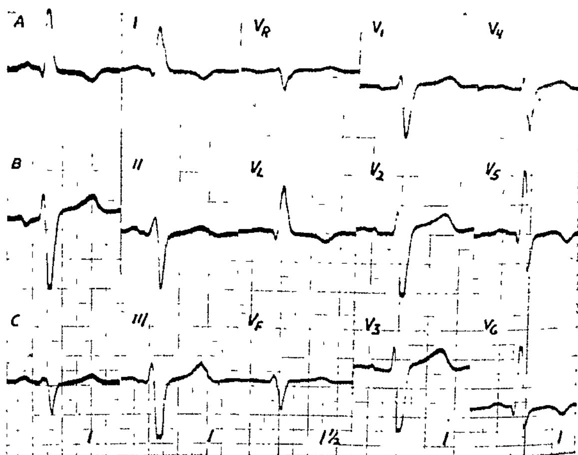
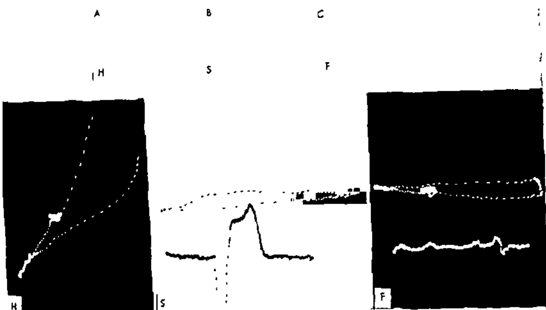


Fig. 4-53. Left ventricular hypertrophy, essential hypertension The QRS loop is more posteriorly (*H*) and superiorly, (*S,F*) oriented, and inscribed counterclockwise with an essentially even spacing of time markers. Point of origin and point of return of the QRS loop do not coincide, resulting in an ST vector which is oriented to right, anteriorly, and slightly inferiorly The T loop is discordant with the QRS loop. The electrocardiogram (5 cm/sec) correlates well with the respective plane projections of the vectorcardiogram. The S waves in V_5 and V_6 result from superior orientation of QRS loops and inferior angulation of their lead lines of derivation or projec-



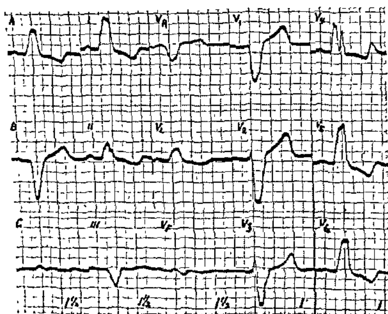


Fig 4-54. Left bundle branch block The vector is posteriorly and horizontally oriented, inscribed clockwise in the *horizontal plane without any anterior deflection The middle section* shows a characteristic slowing of time markers The ST vector is oriented anteriorly, to the right, and slightly superiorly with the T loop discordant with the QRS loop. The electrocardiogram (5 cm/sec) shows the corresponding changes: QS in V_1, slow plateau and upstroke in leads I, V_5, and V_6.

in an S-T segment deviation in the routine electrocardiogram.

In the presence of *left bundle branch block,* the time markings are much closer together. This increased proximity is usually seen in the middle and late portions of the QRS loop (Fig. 4-54). The main portion of the QRS *loop in the horizontal plane projection is* inscribed in a clockwise direction, in contradistinction to the rotation found in normal individuals and in those with left ventricular hypertrophy. The QRS loop is oriented posteriorly, to the left, and often superiorly. In each projection, there is increased proximity of the time markings. The T loop is usually oriented opposite to the QRS loop, and the QRS loop fails to close prior to the inscription of the T loop

In both *left ventricular hypertrophy* and *left bundle branch block,* the T wave is inverted in the electrocardiogram whenever the ventricular complex is essentially upright since the T and QRS loops are oriented in opposite directions in each plane.

Many forms of conduction disturbances have been encountered, distinctly apart from so-called left bundle branch block. Some have been discussed before, others await further study and thought.

Routine electrocardiography may fail to distinguish *right ventricular hypertrophy* from *right bundle branch block.* The precordial lead patterns are at times similar, RSr′ or rSR′ patterns may be present over the right precordium in both entities. The vectorcardiographic patterns of each are distinctive, however. *Atypical right bundle branch block* (*Wilson type*) is characterized by alterations which are usually confined to the terminal portion of the QRS loop (Fig. 4-55). This terminal

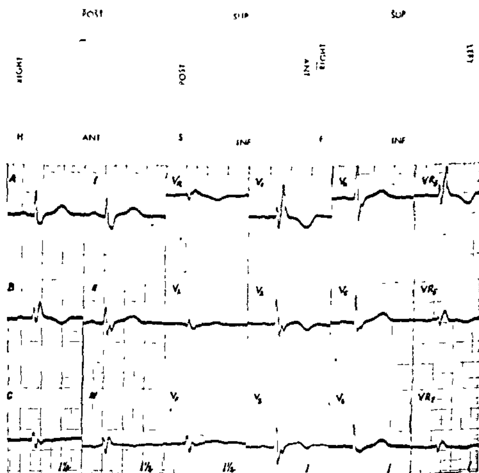


Fig. 4-55. Right bundle branch block. The QRS loop in the horizontal plane is inscribed counterclockwise with a slowed right anterior appendage. The T loop is in the opposite direction. The electrocardiogram (5 cm/sec) shows accordingly a broad S wave in leads I, V_4, and V_5, rsR′ in V_1, $VR_{3,5,7}$. The T waves are inverted in right-sided chest leads and upright in left-sided chest leads.

portion in each projection is increased in duration, is slow and irregular in contour, and is directed to the right and anteriorly. The terminal portion of the QRS loop produces the slow, widened S wave of leads I and V_6, and the R′ or late R wave of lead V_1, and may coexist with any normal or pathological variety of the QRS loop.

In *right ventricular hypertrophy*, there is no evidence of a significant transient slowing of conduction. The QRS loop is oriented to the right, anteriorly, and inferiorly, in mild degrees of right ventricular preponderance; to the right, anteriorly, and superiorly, in more severe degrees, and to the right, posteriorly, and superiorly, in most marked degrees. When the right ventricular preponderance is mild to moderate (Fig. 4-56), the horizontal projection is characterized by an initial small deflection directed to the right and anteriorly, followed by a large deflection to the left and somewhat posteriorly, then sharply to the right and anteriorly with a clockwise return to the points of origin. A unipolar electrocardiogram recorded over lead V_1 will reveal rsR′ patterns identical to those encountered in patients with atypical right bundle branch block. With increasing degrees of right ventricular hypertrophy, promi-

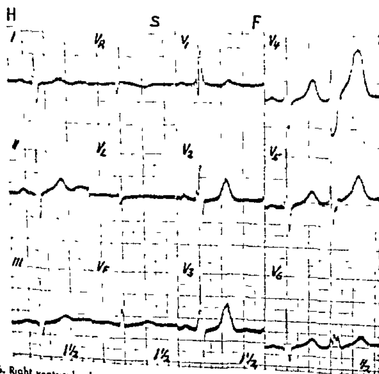


Fig. 4-56. Right ventricular hypertrophy: valvular pulmonic stenosis with intact septums. The vector loop in the horizontal plane is rotated clockwise without any delay of its terminal segment (H,F). The electrocardiogram (5 cm/sec) shows an rsR′ configuration in lead V_1.

in an S-T segment deviation in the routine electrocardiogram.

In the presence of *left bundle branch block,* the time markings are much closer together. This increased proximity is usually seen in the middle and late portions of the QRS loop (Fig. 4-54). The main portion of the QRS loop in the horizontal plane projection is inscribed in a clockwise direction, in contradistinction to the rotation found in normal individuals and in those with left ventricular hypertrophy. The QRS loop is oriented posteriorly, to the left, and often superiorly. In each projection, there is increased proximity of the *time markings. The T loop is usually oriented* opposite to the QRS loop, and the QRS loop fails to close prior to the inscription of the T loop.

In both *left ventricular hypertrophy* and *left bundle branch block,* the T wave is inverted in the electrocardiogram whenever the ventricular complex is essentially upright since the T and QRS loops are oriented in opposite directions in each plane.

Many forms of conduction disturbances have been encountered, distinctly apart from so-called left bundle branch block. Some have been discussed before, others await further study and thought.

Routine electrocardiography may fail to distinguish *right ventricular hypertrophy* from *right bundle branch block.* The precordial lead patterns are at times similar, RSr′ or rSR′ patterns may be present over the right precordium in both entities. The vectorcardiographic patterns of each are distinctive, however. *Atypical right bundle branch block* (*Wilson type*) is characterized by alterations which are usually confined to the terminal portion of the QRS loop (Fig. 4-55). This terminal

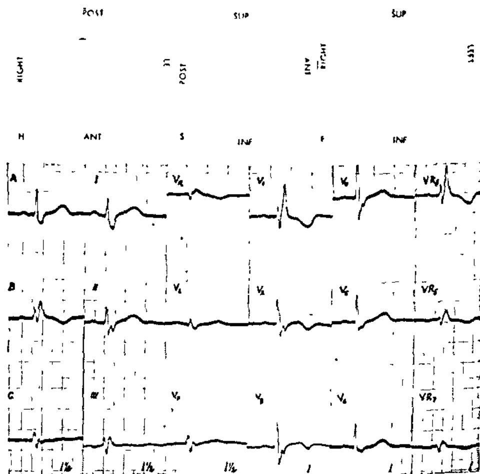


Fig. 4-55. Right bundle branch block. The QRS loop in the horizontal plane is inscribed counterclockwise *with a slowed right anterior appendage. The T loop is in the opposite direction* The electrocardiogram (5 cm/sec) shows accordingly a broad S wave in leads I, V_4, and V_5, rsR′ in V_1, $VR_{3,5,7}$. The T waves are inverted in right-sided chest leads and upright in left-sided chest leads.

existence of left ventricular hypertrophy could not be invoked to explain the superior orientation (or left axis deviation).

MYOCARDIAL INFARCTION

In the normal heart, one records essentially the balance generated by the opposing forces of the anterior and posterior walls, the diaphragmatic and superior aspects, and the right and left aspects of the heart. When infarction of any part of the heart occurs, the damaged area may be considered as electrophysiologically inert. As a result, there is no contribution of this area to the total resultant electromotive forces, and there is an apparent augmentation of the forces generated by the diametrically opposite area. For example, an infarction localized to the anterior aspect of the heart (Figs. 4-60, 4-61) will augment the forces acting posteriorly, while an infarction of the diaphragmatic aspect will augment the forces acting superiorly. Since the QRS loop represents all the emf of the heart, it will be oriented posteriorly when an anterior infarc-

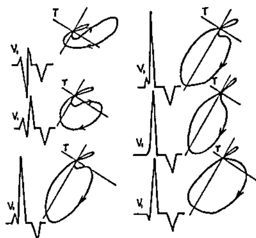
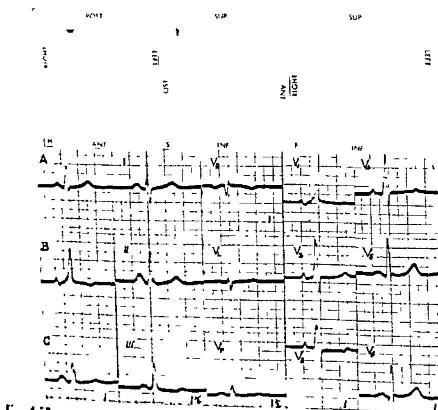


Fig. 4-59. The initial vector in right ventricular hypertrophy and the resultant projection of lead V_1.



...rked pulmonary hypertension. The ... right, turning to the left and then ...e left and inferiorly. The P loop is ...gram (5 cm/sec) accordingly shows ... and biphasic P waves in lead V_1.

nent R waves are inscribed over the right precordium (Fig. 4-57) and essentially negative ventricular complexes over the left (Fig. 4-58).

The initial part of the vector loop is probably inscribed by septal activation alone. It is directed to the right, anteriorly, and somewhat superiorly. The septal vector in right ventricular hypertrophy often becomes directed towards the left, sometimes even markedly so. This will result in low R waves, isoelectric segments, or even Q waves in right-sided chest leads.

In *mitral valve disease*, vectorcardiographic studies appear inconsistent. Although severe *right ventricular hypertension* exists, the vectorcardiogram may reveal a normal balance. In other cases, the correlation to right ventricular pressures is similar to that encountered in congenital heart disease (Figs. 4-58 and 4-59).

The very frequent association of *superior orientation* (frontal and sagittal plane) with *anterior orientation* in the horizontal and sagittal plane in cases of persistent atrioventricular canal (ostium primum, cushion defect) has proved to be of great diagnostic importance. When marked left axis deviation is paired with rsR' complexes in lead V_1, and right bundle branch block is excluded through vectorcardiographic examination, the diagnostic probability of this malformation is very high. Curiously enough, this does not necessarily represent an instance of combined hypertrophy since it seems to exist in the absence of mitral clefts and mitral insufficiency. Therefore, the co-

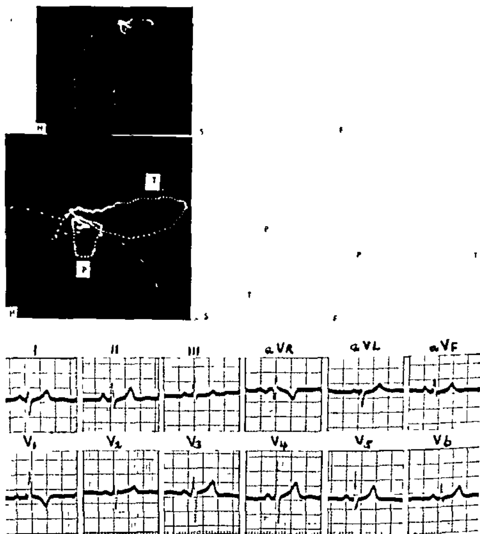


Fig. 4-57. Right ventricular hypertrophy Tetralogy of Fallot in adulthood. In the horizontal plane the QRS loop moves initially to the right, turning to the left and then anteriorly The T loop is to the left and inferiorly. The P loop is anteriorly and inferiorly, suggesting right atrial preponderance (hypertrophy). The electrocardiogram (2.5 cm/sec, 1 cm/mv) shows accordingly an RR' in lead V_1.

cardiogram, i.e., there will be no diagnostic Q waves.

S-T SEGMENT

trocardiogram The direction and degree of this deviation may be determined by drawing a line from the dipole center "E" of the vectorcardiogram to the onset of the slowly inscribed T loop. This line represents the S-T vector, with the proximal end at "E" and the distal end as indicated. The orientation of this vector determines in which leads the S-T segment deviates. If this vector is directed to the right and

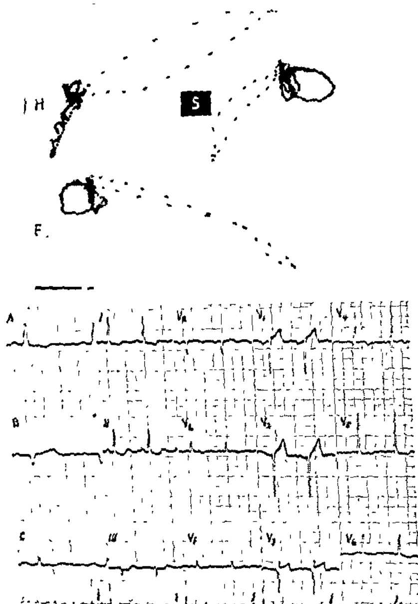


Fig. 4-61. *Myocardial infarction, anteroseptal, subacute stage. In the horizontal vectorcardiogram, the QRS loop turns immediately to the left and posteriorly. The T loop is anteriorly oriented, of round shape and essentially symmetrical. The latter presents a rather characteristic appearance for the T wave changes within the acute or subacute phase. The electrocardiogram (leads A, B, C recorded at 5 cm/sec; the remainder at 2.5 cm/sec). The QS complexes are recorded in leads V_1 to V_3. The rounded appearance and symmetrical inscription of the T loop has no electrocardiographic counterpart in this record.*

tion occurs, and superiorly when a diaphragmatic infarction occurs (Fig. 4-62). Q waves are registered in routine unipolar leads over the site of infarction since the forces are directed away from the infarcted area and, therefore, away from the electrode. R waves are usually registered opposite the site of the infarction since the forces are augmented in the area diametrically opposite to the infarcted area It is not the author's purpose to describe the characteristics of the vectorcardiogram for each site of myocardial infarction; however, it is of value to indicate how a consideration of myocardial infarction on a vector basis can explain some otherwise confusing electrocardiographic patterns.

Since prominent R waves are recorded opposite the site of infarction, the prominent R waves recorded in lead VR in extensive *apical infarction* need not be explained by rotational factors but by loss of apical electromotive forces Prominent R waves in leads V_1 and V_2 can occur with *posterolateral infarctions*, while *diaphragmatic infarctions* may be accompanied by prominent R waves in supracardiac esophageal leads.

There may be no evidence of infarction in routine electrocardiograms in some patients, but the vector loop may be displaced anteriorly In such instances, *infarction of the posterior wall* should be suspected (Fig. 4-63).

It should be realized that, under the vector concept, the "window effect" for the origin of the Q wave is no longer tenable. The Q wave was regarded as the reflection of a left ventricular cavity potential through a "window" within the left ventricular wall: the electrically inert area of the myocardial infarction. The shift of the vector loop may not be effected in the form of a localized marked deviation, away from the exploring unipolar electrode, but may be effected more widely and gradually. Although distinct abnormalities may appear in the spatial vectorcardiogram, they may not present evident abnormalities in the electro-

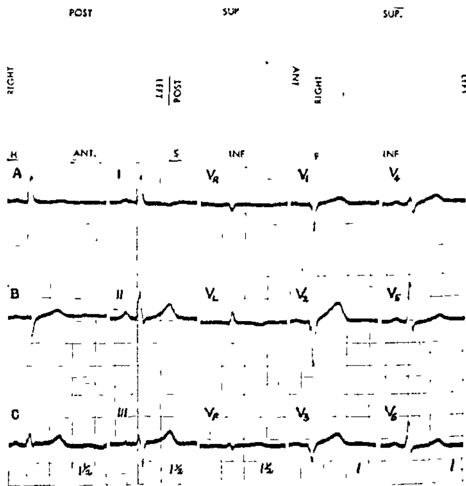


Fig. 4-60. Myocardial infarction, anteroseptal. The initial vector goes immediately to the left and slightly posteriorly, to continue in a counterclockwise direction. The T loop is anteriorly oriented. The electrocardiogram recorded at 5 cm/sec shows accordingly a QS complex in lead V_1 and a notched downstroke in leads V_2 and V_3.

cardiogram; i.e., there will be no diagnostic Q waves.

S-T SEGMENT

Whenever the *QRS loop* fails to close prior to the inscription of the T loop, there is a deviation of the S-T segment registered in the electrocardiogram. The direction and degree of this deviation may be determined by drawing a line from the dipole center "E" of the vectorcardiogram to the onset of the slowly inscribed T loop. This line represents the S-T vector, with the proximal end at "E" and the distal end as indicated. *The orientation of this vector* determines in which leads the S-T segment deviates. If this vector is directed to the right and

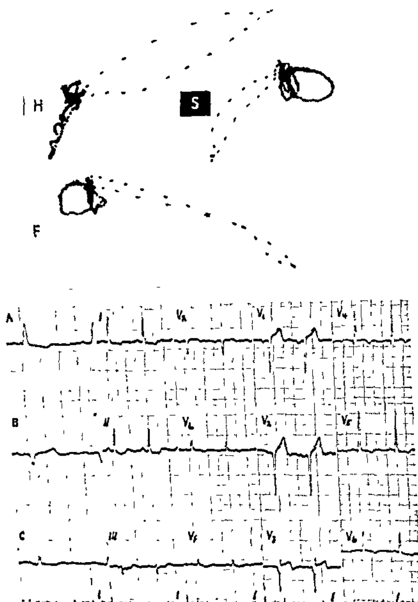


Fig. 4-61. Myocardial infarction, anteroseptal, subacute stage. In the horizontal vectorcardiogram, the QRS loop turns immediately to the left and posteriorly. The T loop is anteriorly oriented, of round shape and essentially symmetrical. The latter presents a rather characteristic appearance for the T-wave changes within the acute or subacute phase. The electrocardiogram (leads A, B, C recorded at 5 cm/sec; the remainder at 2.5 cm/sec). The QS complexes are recorded in leads V_1 to V_3. The rounded appearance and symmetrical inscription of the T loop has no electrocardiographic counterpart in this record.

superiorly, the S-T segment will be recorded as elevated in leads VR and V_1 while the S-T segment will be depressed in leads I, VL, VF, and leads taken over the left precordium. Although the S-T segment deviations in routine electrocardiograms have an essentially similar distribution in left ventricular hypertrophy, left bundle branch block, and acute coronary insufficiency, the spatial orientation of the S-T vector differs distinctly in these three conditions.

In *acute myocardial infarction*, the S-T vector clearly points to the site of the current of injury with the polarity as it appears during ventricular activation. The findings in instances of *fibrinous pericarditis* are similar but without associated changes of the QRS loop.

THE T LOOP

The electrical expression of the process of repolarization is given by the T loop In certain lower species, such as the frog, the se-

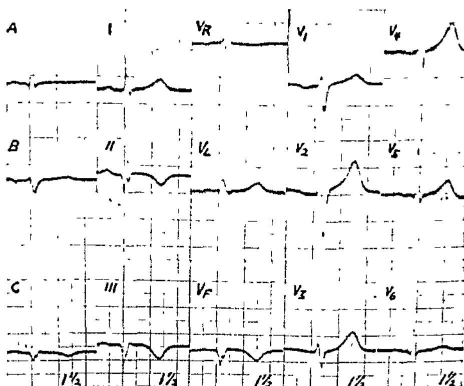


Fig. 4-62. Myocardial infarction, diaphragmatic. In the frontal and sagittal plane projections the vectorcardiogram is seen to be superiorly displaced, with a clockwise inscription in the frontal plane and a counterclockwise inscription in the sagittal plane. The T loop is superiorly oriented. The horizontal plane projection remains rather unaffected The electrocardiogram (5 cm/sec) shows accordingly deep Q waves in leads II, III, and VF.

quence of repolarization is similar to that of depolarization in that the first area depolarized is also the first to be repolarized. The T loop, which is the result of repolarization will, therefore, be *oriented* along the same axis but will be *opposite in polarity* as compared to the QRS loop which is the result of depolarization. In the warm-blooded species, the spatial orientation of the QRS and T loops will not coincide exactly; with the result that there is a rather narrow range of angular deviation due to an altered time-sequence of repolarization in relation to depolarization. Both processes differ, furthermore, in the speed with which the emf is generated. The duration of the process of repolarization is not necessarily *identical for* each muscle area or layer. Localized *disturb*ances of the repolarization process may become evident by an altered contribution towards the T loop so that its spatial orientation is altered in relation to the long axis of the QRS loop. Abnormal degrees of angular deviation between the QRS and T loops can be recognized before abnormal T waves are recorded in extremity or chest leads since a relatively large angular deviation is necessary before abnormal T waves

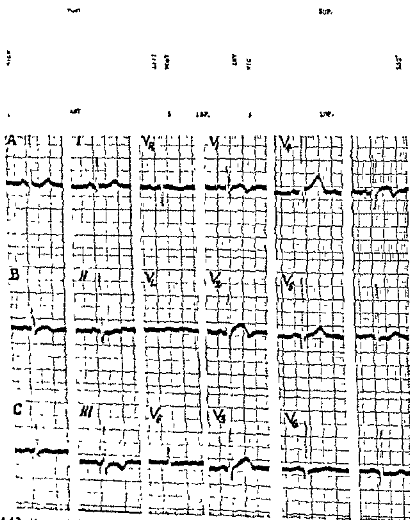


Fig. 4-63. *Myocardial infarction, posterior wall* In the horizontal and sagittal plane projections, the vector is seen to be all *anteriorly displaced, retaining,* however, the normal directions of inscription, i.e., counterclockwise *in the horizontal plane and clockwise in the sagittal plane.* The electrocardiogram (2.5 cm/sec) shows accordingly high R waves in lead V_1. Although high R waves in these leads are suggestive of *posterior infarction*, this diagnosis requires vectorcardiographic confirmation.

are recorded. The yield of diagnostic vectorcardiograms in patients with angina pectoris due to coronary sclerosis is, therefore, greater than with routine electrocardiograms.

Alterations of the spatial orientation of T loops caused by myocardial disease are distinctly different from those due to quinidine, emetine, Fuadin, and hypopotassemia, moving *anteriorly* in the former and mostly *posteriorly* in the latter.

WOLFF-PARKINSON-WHITE SYNDROME

The characteristic element of aberrant atrioventricular and interventricular conduction, the delta wave, is shown most clearly in the spatial vectorcardiogram (Fig. 4-64). Its absence probably precludes the diagnosis, since short P-R intervals have been encountered in cases of left bundle branch block. The observation of Wolff et al., that aberrant atrioventricular

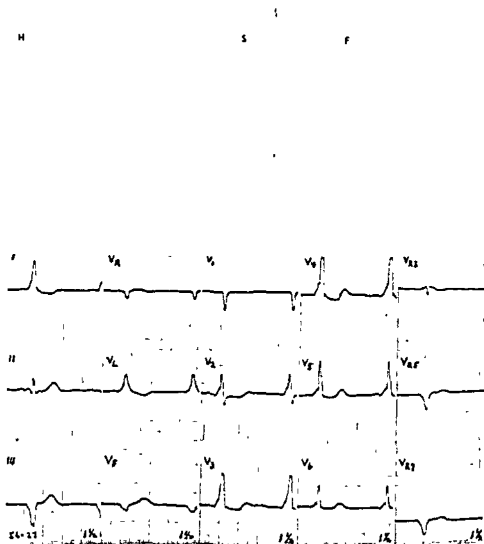


Fig. 4-64. Wolff-Parkinson-White syndrome In the horizontal and frontal plane projections, the initial segment of the QRS loop is seen to be slightly more slowly inscribed by a distinct separation of this loop from the rapid segment In the frontal plane the vectorcardiogram is superiorly oriented with a partially discordant T loop The electrocardiogram (5 cm/sec) shows the characteristic appearance of the Wolff-Parkinson-White conduction defect The QRS complexes show distinct, slurred upstrokes in leads I and V_2 to V_6. The latter is the electrocardiographic counterpart of the initial slow segment of the vector loop The P-R intervals are short throughout and secondary S-T and T changes are seen.

conduction can be found in association with so-called atypical right *bundle branch block*, can be confirmed. In spite of a large number of cases investigated, *without* and with all varieties of heart disease, features of sufficient diagnostic value have *not been found* as long as the abnormal conduction prevailed. Quinidine sulfate administered *intravenously* in *judicious doses* has suppressed aberrant conduction in most instances in the author's experience. This may become important in the diagnosis of congenital heart disease but should not be considered for cases of myocardial infarction.

THE P LOOP

In the past, instrumental limitations made a satisfactory study of the P loop difficult. Greatly improved instruments have made it *possible* to record detailed curves. Mitral valve disease, right-sided congenital cardiac defects, *and* pulmonary disease have *shown* rather characteristic P loops. They are triangular, oriented inferiorly in a sagittal plane in *left atrial enlargement*, and anteriorly and somewhat inferiorly, in *right atrial enlargement* (*Fig.* 4-65).

THE VALUE OF VECTORCARDIOGRAPHY

The vector concept and spatial vectorcardiography *have made a twofold* contribution. Vectorcardiography has become (1) the method of choice for teaching clinical electrocardiography, and (2) a valuable diagnostic tool, as an *adjuvant to clinical electrocardiog-*

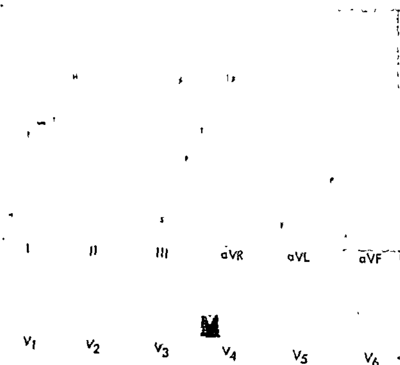


Fig. 4-65. Tricuspid stenosis. The P loop is of high voltage and increased duration and is entirely anteriorly oriented. This is characteristic for right atrial preponderance (hypertrophy). The electrocardiogram (2.5 cm/sec; 1 cm/mv) shows P waves of very high voltage in leads V_1, V_2, and V_3.

raphy, mainly through its graphic presentation of phase relationships not presented in conventionally recorded electrocardiograms. The vector concept is unitarian, treating all electrocardiographic leads as derivations of the spatial cardiac vector. These are to be viewed as projections of the spatial cardiac vector upon the lead lines of derivation. Its basis is the dipole theory as first proposed in its elementary form by Einthoven. The evidence presented in recent years in support of the dipole theory is most convincing.

The unitarian character of the vector concept allows the presentation of all electrocardiographic leads to be related to each other as derivatives of the single spatial cardiac vector. The memorizing of patterns and configurations with such a mode of teaching is no longer necessary. The cardiac vector contains all the information about the balance of forces at each instant. This balance is well established for the normal heart showing great consistency in its basic characteristics with few and minor variations. The considerable variability of the normal electrocardiogram is due to the fact that a normal spatial cardiac vector will produce differing projections through even minor changes of its spatial position in relation to the fixed lines of lead derivations. *Normalcy* is presented through the spatial cardiac vector in a simple way while electrocardiographically the recognition of a *normal* electrical behavior of the heart is more complex. Thus, the numerous electrocardiographic facets of normalcy can be simply visualized as caused by altered orientation of a normal cardiac vector in regard to a fixed lead system. Similarly, deviation from its normal characteristics can be ascribed to specific pathological entities The analysis of even the most complex set of electrocardiograms offers few difficulties when the spatial vectorcardiogram is available

It should be realized that the determination of cardiac position and rotation from the electrocardiogram has no validity The configuration of a given lead does not depend upon the cardiac chamber facing it but upon the projection of the cardiac vector to the lead line of derivation. The relationship of the spatial position of the cardiac vector to the cardiac position is too inconsistent to retain significance Furthermore, more direct means are available for learning a patient's cardiac position.

Similar caution should be applied to continued usage of the terms "intrinsic" or "intrinsicoid" deflections. At the present state of knowledge, it cannot be considered a signal of the arrival of the excitation wave in the area under the exploring electrode, but a representation of the turning point of the cardiac vector in relation to the line of derivation of the lead employed.

FUTURE DEVELOPMENTS

The stimuli provided in recent years to extend renewed investigations in the varied foundations of experimental and clinical "electrocardiology," are going to provide many new thoughts, approaches, and facts. Vector integration, under investigation in the author's and other laboratories, will lead to many new ideas in regard to spatial analysis and quantitation of changes.

A purist's approach to vectorcardiography does not appear to be a productive one With the information desired from the spatial vectorcardiogram at present, the available techniques —in the author's hands the "cube" technique of electrode placement—have proved reliable and most adequate Refinements proposed have emanated from investigators who were not adequately aware of the scope of information desired. For the biological variations encountered, the existing techniques are of ample exactness.

Should work with vector integration and other modes of quantitation suggest greater exactness to be desirable, correcting schemes for the existing systems (at least for the "cube" technique) can be devised and used, since the necessary steps are well evolved and known. So far, even for vector integration, the need for greater accuracy has not arisen.

It is felt that the sources of error and devia-

3

Studies of the peripheral circulation

Plethysmography

HERBERT HENSEL

The Capillary Circulation

RICHARD E. LEE

PLETHYSMOGRAPHY

Plethysmography means "recording of volume." In particular, it means recording of the volume of a part of the body with respect to time. If one assumes that the volume of bloodless tissue remains constant (this is approximately true for a short period of time), the changes in volume of an organ correspond to changes of its blood content. Though this principle seems simple, it may be difficult to express changes of volume in a theoretical way and to draw conclusions pertaining to the rate of blood flow. This is for the following reasons:

1. The blood volume of a certain part of the body is not static but is in a dynamic state because of the relationship between inflow and outflow; a constant volume would represent a steady state between inflow and outflow.

2. The volume measured by plethysmography represents the sum of the volumes of various parts of tissue in which the volume and flow of blood differ considerably, and sometimes behave antagonistically.

This is particularly true when the plethysmograph includes skin and muscle, because opposite reactions may occur in these tissues, for instance during intravenous infusion of epinephrine, indirect warming, the smoking of a cigarette, and the application of psychogenic stimuli. In man, only those parts of the body which can be placed in a plethysmograph can be used. This means mainly the extremities or their parts. Plethysmography of the ear lobes can be performed. In persons with open defects of the skull, plethysmography of the brain can be performed. Plethysmography of the abdominal organs has been tried by means of a balloon introduced into the colon. However, it is difficult to interpret the results obtained in terms of intraabdominal blood volume.

In *direct plethysmography*, the volume changes of a part of the body are recorded. The latter is placed in a suitable plethysmograph, i.e., a rigid container filled with water or air having an opening which fits tightly over the part of the body to be examined. At one end, the plethysmograph is connected, through an opening, with an instrument recording volume.

When the volume of the bloodless tissue remains constant with respect to time, the following formula can be used.

$$V = V_0 + \Delta V \qquad (1)$$

where V_0 = initial volume
ΔV = change of volume during time (t)

ΔV is also the difference between the arterial inflow V_a and the venous outflow V_v.

$$\Delta V = V_a - V_v \qquad (2)$$

Differentiating the curve of volume with respect to time yields the rate of volume change as a function of time dV/dt. This is the difference between rate of blood inflow dV_a/dt and rate of blood outflow dV_v/dt.

$$\frac{dV}{dt} = \frac{dV_a}{dt} - \frac{dV_v}{dt} \qquad (3)$$

In *occlusion plethysmography*, the venous outflow is blocked for a short period of time so that V_v has the value of 0. The subsequent increase in volume is a direct measure of the inflowing arterial blood.

$$V_a = \Delta V \qquad (4)$$

The steepness of increase in volume, i.e., the differential quotient of volume with respect to time, is then a measure of the rate of blood inflow.

$$\frac{dV_a}{dt} = \frac{dV}{dt} \qquad (5)$$

As the rate of volume change according to formula (3) is equal to the difference between the rates of inflow and outflow, one can calculate the rate of venous outflow.

$$\frac{dV_v}{dt} = \frac{dV_a}{dt} - \frac{dV}{dt} \qquad (6)$$

The methods of *indirect plethysmography* are not worthy of the name "plethysmography" in the true sense of the word because they do not record directly the changes in volume. Here the changes in volume are observed through changes in girth (strain-gage plethysmography), variations in the absorption of light (photoelectric plethysmography), or changes in electrical impedance of the tissue (impedance plethysmography).

HISTORY

Data concerning the historical development of plethysmography can be found in Johnson, Berry, and Barcroft and Swan Plethysmography is one of the oldest physiological experimental methods The oldest apparatus was built by Glisson (1677) and Swammerdam who, by their experiments, disproved the existing opinion that a skeletal muscle became inflated during contraction. Poiseuille (1828) used a plethysmograph for measuring the volume changes of an artery during contraction of the heart. Piégu (1846) and Chelius (1850) studied by means of plethysmographs the circulatory and respiratory changes of volume of human limbs. The first plethysmograph with graphic recording was described by Buisson (1862). Particularly well-known and much used was the plethysmograph of Mosso (1875). This consisted of a glass cylinder to enclose the forearm. The base of the limb was secured by a rubber cuff closing over the opening through which the arm was inserted. The cylinder was filled with water and the changes of volume were transmitted by water to a float which recorded a graph on a revolving cylinder. In 1905 Brodie and Russell found that the plethysmograph could be used, not only for the purpose of recording volume changes, but also for the recording of the rate of blood inflow. They used a simple modification of the plethysmographic method which permitted quantitative determination of the rate of flow. In principle, this consists of blocking briefly the vein of an organ enclosed within the plethysmograph. All venous blood is then retained within the plethysmograph and causes a rise of the recording pen. If the rate at which the pen rises is calibrated, one can determine the rate of flow into the veins. In the application of such a method, it is essential that the venous block is not maintained long enough to impede the flow through the capillaries Under ordinary conditions, the veins are never completely filled, so that it is possible to store in them a small extra quantity of blood without checking the inflow from the capillaries. This possibility is excluded as long as the lever of the recorder continues to rise at a uniform rate during the whole period of observation. If this is not the case, and the tracing becomes concave toward the abscissa, then the blockage has been unduly prolonged and the observation must be discarded.

It is not known whether Brodie and Russell actually performed experiments on blood circulation on human limbs. Their idea was followed up by Hewlett and van Zwaluwenburg (1909). The plethysmograph designed by them was first filled with air, but later the air was replaced by water kept at constant temperature. Venous occlusion was achieved by a narrow pneumatic cuff placed on the upper arm Lewis and Grant later designed a plethysmograph which enclosed only a segment of the forearm This instrument was filled with water at constant temperature and was closed by rubber cuffs on both ends Krogh achieved isolation of the enclosed arm by covering it with a loose sleeve of thin latex rubber fixed at each end around a central hole in a soft rubber diaphragm The first occlusion plethysmograph for the hand was described by Freeman (1935) Later, Grant and Pearson (1938) stated that the hand plethysmograph registers mainly the blood flow of the skin, whereas plethysmography of the forearm reg-

isters mainly the blood flow of the muscles. However, this view had to be revised. Later, only the muscular part of the forearm was enclosed while the hand was excluded by means of a pneumatic cuff applied to the wrist. This increased the use of the apparatus for the study of muscle blood flow

TECHNICAL DATA

Various types of plethysmographs have been developed They differ according to their various purposes. However, prototypes can be described

Several points are important in the construction of a plethysmograph. (1) fitness for the shape and size of the part of the body to be examined, (2) close isolation of the enclosed part without interference with the circulation, (3) as far as possible, rigid material of the tightening device, so that the volume changes can only be transmitted in one direction, (4) controllable temperature within the plethysmograph, (5) visibility of the enclosed part of body (not always required), (6) low hydrostatic pressure within the plethysmograph, (7) sensitive recording apparatus (not always required), (8) proper position in order to avoid disturbances in circulation and fatigue to the patient.

The various types of plethysmographs differ mainly in the special construction for various parts of the body, in the way they are made tight around the enclosed organ, and in the use of air or water.

Plethysmographs for the Calf and Forearm These are cylinders with openings on both ends through which the extremities can be inserted The type shown in Fig 4-66A has proved useful. Tight fitting is achieved by means of a thin rubber sleeve glued on both ends to soft rubber diaphragms The latter are made stiffer by metal plates (Lewis and Grant, Abramson et al., Barcroft et al) The plethysmograph is filled with water which flows through a jacket and is kept at constant temperature by means of a thermostat. The plethysmograph has a transparent top through which the water level is visible Attached to this is an instrument recording the volume

A flexible plethysmograph for clinical purposes has been described by Dohn et al It consists of a double-walled rubber bag for a segment or a distal part of an extremity The pressure changes of the inflated bag are used to record volume changes.

Plethysmographs for the Hand and Foot. The device described above can be used, but the plethysmograph is closed on one side. The hand is placed in a large rubber glove, the rim of which is fixed around the opening of the plethysmograph (Barcroft and Swan). Another type of hand plethysmograph which can be slightly modified for the foot is shown in Fig. 4-66B (Rothlin and *Bluntschli*). The plethysmograph has a metal jacket through which flows water at constant temperature The walls are made of glass so that the enclosed organ is visible. Either the hand or the foot rests on a suitable support within the *plethysmograph*. Fitting is achieved by cotton wool and Vaseline inside a plaster cuff which protects the extremity against pressure. Tightness between the plaster cuff and the wall of the plethysmograph is achieved by an inflated rub-

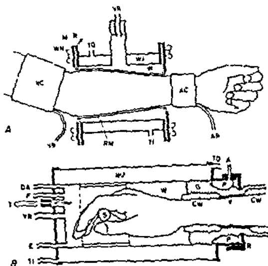


Fig. 4-66. A Occlusion plethysmograph for the forearm. WJ, water jacket; TI and TO, inflow and outflow of thermostat water; W, inner water filling; F, flange, R, soft rubber diaphragm; RM, thin rubber membrane; M, metal plate; WN, wing nuts, VC, venous occlusion cuff; VP, connection with pressure reservoir at 60 mm Hg, AC, arterial cuff, AP, connection with pressure reservoir at 200 mm Hg; VR, attachment of recording instrument (After Barcroft and Swan, modified.) B Hand plethysmograph. WJ, water jacket; TI and TO, inflow and outflow of thermostat water; W, inner water filling, G, plaster cuff; CW, cotton wool; V, Vaseline petroleum jelly; P, pneumatic cuff; A, tube for compressed air; R, ring, S, support for hand; F, filling shafts; E, emptying shafts; DA, valve; T, thermometer; VR, attachment of volume recorder. (From Rothlin and Bluntschli.)

In *occlusion plethysmography,* the venous outflow is blocked for a short period of time so that V_v has the value of 0. The subsequent increase in volume is a direct measure of the inflowing arterial blood.

$$V_a = \Delta V \tag{4}$$

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voltage of about 10 μv, which is well recorded by a galvanometer of average sensitivity.

The method has the following advantages. The instrument is light and handy. The recording unit is connected to the recording instrument only by conducting wires. There are no disturbances associated with compression or inadequate sealing of the plethysmograph. The recording can be made under physiological conditions, even under the clothes and in persons moving about. Furthermore, recording is possible on very short extremity segments, the volume changes being given in per cents of the starting or initial volume. Thus, special measurement of the volume of the segment can be omitted. A disadvantage is represented by the fact that there is no direct measurement of volume and that the test can be done only on parts of the body with approximately circular cross sections, not on hands or feet. Another objection is that, in occlusion plethysmography, the venous blood can accumulate in parts beyond those measured. In general, however, the correspondence of strain-gage plethysmography with direct measurement of volume by occlusion plethysmography is satisfactory (Whitney, 1953).

PHOTOELECTRIC PLETHYSMOGRAPHY

In this type of indirect plethysmography, the blood flow is estimated according to absorption of light by the tissue. Matthes and Gross proved that, with *infrared light* having wave lengths of 750 to 900 mμ, the absorption of light *by a transilluminated part of the body* changes almost entirely with its blood content. *Conversely, the absorption of infrared light* is almost independent of oxygen saturation of the blood. According to Kramer and Schulze, the absorption of light by tissue as a function of the blood content follows the *Lambert-Beer law*, so that the blood flow can be expressed as follows

$$c = K \log \frac{I}{I_0} \tag{8}$$

when K = a constant
I = quantity of light
I_0 = amount of light which passes through tissue
c = the blood content

The photoelectric plethysmographs have the advantage of not interfering with circulation and rendering possible an accurate registration of peripheral pulse volume. According to Matthes and Gross and Matthes (1951; 1952), the ear lobe, the tip of a finger or toe, and so forth, are directly transilluminated. *The peripheral* parts are screened, if possible, in order to avoid interference from positional changes. The light falls on a photoelectric cell sensitive to infrared rays and is recorded by a high-frequency galvanometer or a suitable electronic apparatus. In the method of Hertzman, the source of light is enclosed in a tube which can be placed *directly on any* area of the skin. It is important that the photoelectric cell *receives only the* light coming through the tissues and no other. The disadvantage of the photoelectric plethysmograph is mainly the difficulty of quantitative calibration. In the method used by Hertzman, there is, moreover, the disadvantage of no exact *definition* of the depth of the transilluminated tissue, while the contact with the skin can interfere with local blood flow. Comparison with direct plethysmography makes possible *a relative* determination of volume. A so-called "filter unit" (absorption of light by a clear glass plate 1.1 mm thick) corresponds to a change of blood volume in the skin of 0.0028 ml/cm² (Hertzman et al., 1947). Volume changes are then *referred to this* unit for measuring by the photoelectric cell. The magnitude of the *pulse volume* of skin and the rate of blood flow have an approximate linear relationship (Burton, 1939; Goetz, 1943, Hertzman et al., 1945). The pulse volume thus permits the approximate evaluation of the blood flow through equation

$$F = KP \tag{9}$$

where F = flow in the skin
P = pulse amplitude, filter units
K = flow equivalent of a filter unit

From this it *follows that* a pulse amplitude of
flow of ap-
There also is
ntent and the
rate of blood flow of the skin, a change of blood content of 0.0012 ml/cm² of skin corresponds to a change of blood flow of 0.1 ml/cm²/min (Hertzman et al., 1947). The disadvantage of this method *is that it is indirect*, under certain pathological conditions, the *relationship* between the obtained result and the blood circulation is questionable (Matthes, 1951).

IMPEDANCE PLETHYSMOGRAPHY

The *principle of this* method is based on the fact that blood volume changes cause changes in the electrical impedance of the tissue (Nyboer, 1950). *Subsequent types of impedance plethysmographs work on* an alternating current of 20 to 175 kc which *is led through* a segment of tissue. In the *differential impedance plethysmograph* (Nyboer et al.), the high-frequency current of 175 kc is *modulated in its amplitude* proportionally to the fluctuation of the impedance. These fluctuations are magnified and rectified. The sensitivity is greater than 0.01 ohm (Fig. 4-67).

Rust-proof rings can be used as electrodes. Im-

ber cuff. The plethysmograph works through water transmission. In other plethysmographs, the isolation is achieved by means of a rubber sponge and a fast-drying cement (Wright and Phelps).

Plethysmographs for Fingers, Toes, and Ears. Plethysmography of fingers and toes is performed mostly at the end phalanx. The finger is placed in a cylinder of suitable size made of glass or metal, with a diameter of 15 to 22 mm. Tight fitting is attained with a mixture of vegetable oil, asbestos, and calcium carbonate (Kappert, 1956). If the finger plethysmograph fits well, the above-mentioned material may be dispensed with. Conversely, this should be used on the toes because of their greater irregularity in shape. The method of choice in both finger and toe plethysmography is filling with air (Goetz; Burton, 1939; Burch; Lund, Kappert, Melrose et al) because the changes in volume are proportionately large. The air also transmits well the contour of the volume pulse, which is important for clinical purposes. Burch et al described a plethysmograph suitable for the upper part of the ear, similar to the finger plethysmograph.

TRANSMISSION AND RECORDING OF VOLUME CHANGES

Large plethysmographs are now filled with water, which is not compressible and, therefore, transmits accurately all changes of volume. Moreover, water allows a better control of temperature On the other hand, the pulsations are considerably decreased by the inertia of the fluid while the hydrostatic pressure acting on the extremities is slightly higher than that in a plethysmograph filled with air (Berry) The decrease of the pulse due to water is unimportant in plethysmography of hand, foot, forearm, or calf, as the vascular network of these parts is large and complex These parts of the body are mostly studied by occlusion plethysmography for which mean rate of blood inflow is sufficient. High hydrostatic pressure on the extremity has to be avoided in order to prevent interference with venous filling The pressure should therefore not be more than a few cm of water: the transmission to the recording instrument can be achieved by either water (Rothlin and Bluntschli; Cerletti) or air. A combined water and air transmission has proved successful (plethysmograph filled with water; transmission through air) (Abramson et al; Wise; Barcroft and Swan). In finger plethysmography, air transmission is the method of choice. During recordings of volume, precautions must be taken to keep the changes of pressure small. Large Marey capsules with a thin rubber membrane, water manometers, piston recorders, float recorders, and capillaries filled with fluid can be used as recording apparatus Instruments with a high coefficient of elasticity, such as small, rigid membranes which react to volume changes only through considerable changes in pressure, should not be used. Goetz uses a horizontal capillary tube containing a drop of colored liquid for recording small volume changes of fingers and toes. The displacements of the drop are photographically recorded as a curve on a moving film. Burton and Burch use a small capsule with a thin rubber membrane on which is glued a small mirror. The movements of the latter are registered on a photographic film For clinical purposes, relatively stiff recording systems are used, such as mechanoelectric transducers (Kappel), condenser manometers, or piezoelectric manometers (Lund). They have the advantage of forming a handy unit with the plethysmograph while the recorder can be situated at a distance and can be connected with the patient by a cable Moreover, the electric transmission allows the use of clinical electrocardiographs or similar instruments The above-described methods do not give a real tracing of volume but are suitable for clinical purposes.

STRAIN-GAGE PLETHYSMOGRAPHY

The strain-gage plethysmograph of Whitney is based on an indirect method in which the girth of a segment of extremity is continuously recorded The changes in volume are proportional to changes in girth According to Whitney (1953), small volume changes in the approximately circular cross section of finger, arm, or calf, can be evaluated through the following equation:

$$\frac{\Delta V}{V} = 2\,\frac{\Delta G}{G} \qquad (7)$$

where V = volume
G = girth of segment

The recording of the circumference must be very precise as the changes are only small fractions of a millimeter When, for instance, the volume of a segment with a girth of 25 cm increases by 1 ml/100 cm³ of tissue, the change of girth is only 0 02 mm or 0 008 per cent Moreover, the recording of girth should occur without changes in tension. Whitney used a thin rubber tube filled with mercury and placed around the [illegible]

[illegible] ter. The bridge is connected with a 2-volt battery and, for 0 01 per cent length changes, gives a

known volume of air into the system with a syringe. After the beginning of venous occlusion, the volume curve rises, first in a linear way, then more slowly; at the end, it runs horizontally when the blood is squeezed under the venous cuff and there is equilibrium between inflow and outflow (Fig 4-68). The venous occlusion should last only during the linear increase of volume At the beginning of occlusion, there is some degree of artifact. A straight line is drawn on the linear part of the curve and the steepness of this line is the measure of the rate of blood inflow in milliliters/minute The part of the extremity is immersed in water and the amount of the water displaced reveals its volume, from this one can figure out the blood flow in milliliters/100 cubic centimeters of tissue/minute. The calculation of an occlusion plethysmogram is more difficult for the finger than for larger parts of the body as volume artifacts are greater and the venous reservoir is smaller. With high blood flow, even the first pulse wave after venous occlusion can appear too small (Hensel and Bender) Burch (1954) evaluates the occlusion plethysmogram of the finger as follows: First the volume artifact is determined by blocking for a short time the blood inflow through an arterial cuff and inflating the venous cuff soon afterwards. The obtained volume vs time curve shows the course of the artifact which is subtracted from the occlusion plethysmogram. The mean volume rate during a pulse wave can be obtained by dividing the increase of volume after the first pulse wave by the time of the pulse wave. However, as the volume rate during the pulse wave varies considerably, it is better to measure the momentary volume rate. For this, the volume vs time curve of the occlusion plethysmogram is differentiated; the slope of the volume increase, $\Delta V/\Delta t$, is measured at intervals of 0 02 to 0.04 sec and plotted as a function of time. The curve obtained represents the volume rate of the arterial inflow as a function of time The volume rate of the venous outflow can be also determined, and the last wave of the pulse volume before venous occlusion is recorded The first derivative of this curve with respect to time, as obtained above,

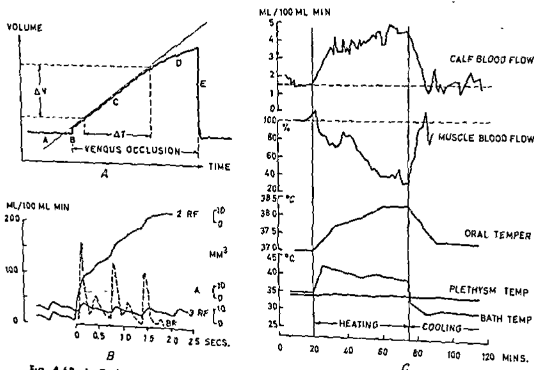


Fig. 4-68 A. Occlusion plethysmogram. *A*, before occluding the veins; *B*, artifact during inflation of the cuff; *C*, linear part of the volume increase; *D*, nonlinear part of the volume increase; *E*, end of the occlusion pressure. B. Occlusion plethysmogram of the finger. *2 RF*, volume increase on the right second finger during venous occlusion, *A*, artifact, *BF*, tracing of flow in right second finger; *3 RF*, pulse volume of the right third finger. At right, measurements in mm³; at left, measure of flow in ml/100 ml/min (From Burch.) C Blood flow in the calf (occlusion plethysmogram) and in the calf muscles (heated thermocouple) during warming and cooling of the body in a bath. (From Barcroft et al)

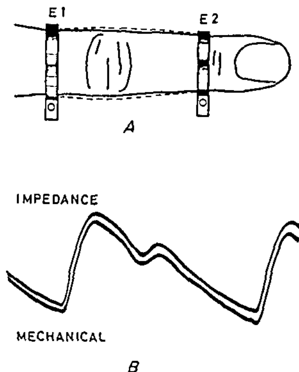


Fig. 4-67. Volume changes in a finger segment with an impedance plethysmograph. A E1 and E2, electrodes on finger. B. Impedance plethysmogram. A mechanical plethysmogram is simultaneously recorded. (From Nyboer.)

pedance plethysmograms can be taken also on flat skin surfaces by means of strips of metal fixed with tape The *rheograph* is an impedance plethysmograph functioning by means of a bridge connection (Polzer and Schuhfried, Kaindl) A Wheatstone bridge is charged with an alternating current of 20 to 30 kc In one branch of the bridge is placed the segment of the tissue and in the other the resistance capacity equalizer. The changes of resistance are amplified, demodulated, and recorded by an electrocardiograph If one places two ring-shaped electrodes at a certain distance from each other around a part of an extremity (Fig 4-67), the following equation can be used for small changes of volume.

$$\frac{\Delta R}{R} = -\frac{\Delta V}{V} \qquad (10)$$

where R = resistance
V = volume

The impedance plethysmogram corresponds well to the mechanical plethysmogram

OCCLUSION PLETHYSMOGRAPHY

Even more important than recording changes of volume is measuring the arterial inflow into a part of the body by the method of Brodie and Russell. For this purpose, the outflow of venous blood is blocked by a pneumatic cuff. The subsequent increase in volume is proportional to the volume of inflowing arterial blood according to Eq. (4). The rate of blood inflow can be obtained according to Eq. (5) from the rapidity of increase in volume. Usually this is given in milliliters per 100 cubic centimeters of tissue/minute. The great advantage of occlusion plethysmography is that it measures arterial blood inflow in an organ directly and quantitatively. On the other hand, there are many disadvantages. (1) The examination requires a certain amount of time, so that continuous recording of rapid changes cannot be performed. (2) It measures the total blood flow in the occluded extremity; differentiation of certain parts of tissue, e g, skin and muscle, is impossible or inaccurate. (3) The venous congestion and the arterial block (in plethysmography of the calf or forearm) can cause errors, which, however, can be minimized by accurate observation of the technical rules.

The venous occlusion pressure must be high enough to block the venous outflow; however, it must be lower than diastolic arterial pressure so that it does not interfere with the arterial circulation, the proper pressure is approximately 60 mm Hg (Barcroft and Swan, 1953, Burch, 1954). The occluding cuff should be as near as possible to the plethysmograph in order to reduce to a minimum accumulation of blood between the two Burch (1954), in performing finger plethysmography, places the cuff directly above the plethysmograph and seals the gap with cement The optimum size for the arm cuff is 6 to 8 cm; for the finger cuff, 6 mm During inflation of the cuff, the plethysmograph shows volume artifacts due to squeezing of the blood from the tissues into the plethysmograph The broader the cuff, and the closer to the plethysmograph, the greater is this artifact The greatest artifacts are observed in finger plethysmography. The inflation of the venous occluding cuff should take place by a rectangular pressure rise For this purpose, one can use a pressure reservoir at about 60 mm Hg which can be suddenly connected with the cuff Burch (1954) uses an electronically controlled valve for finger plethysmography The valve is triggered by the pulse of the contralateral finger and can be set at any point of the pulse wave In occlusion plethysmography of the forearm and calf, the arterial circulation of the hand or foot is respectively isolated by an arterial cuff for about one minute before starting venous occlusion, so that no blood from the distal part reaches the plethysmograph. The inflation of this cuff is achieved from another pressure reservoir set at 200 mm Hg. The *occlusion plethysmogram* is obtained as follows (Fig 4-66A). Before or after the experiment, the recording instrument is calibrated by injecting a

known volume of air into the system with a syringe. *After the beginning* of venous occlusion, the volume curve rises, *first in a linear way, then more slowly; at the end, it runs horizontally when the blood* is squeezed under the venous cuff *and there is* equilibrium between inflow and outflow (Fig. 4-68) The venous occlusion should last only during the linear increase of volume At the beginning of occlusion, there is some degree of artifact. A *straight line* is drawn on the linear part of the *curve and the steepness of this line is the measure of the rate of blood inflow* in milliliters/minute The part of the extremity is immersed in water and the amount of the water displaced reveals its volume, from this one can figure out the blood flow in milliliters/100 cubic centimeters of tissue/minute. The calculation of an occlusion plethysmogram is more difficult for the finger than for larger parts of the body *as volume artifacts are greater and the venous reservoir is smaller* With high blood flow, even the first pulse wave after venous occlusion can appear too small (Hensel and Bender). Burch (1954) evaluates the occlusion plethysmogram of the finger as follows. First the volume artifact is determined by blocking for a short time the blood inflow through an arterial cuff and inflating the venous cuff soon afterwards The *obtained volume vs* time curve shows the course *of the artifact which is subtracted* from the occlusion plethysmogram. The mean volume rate during a pulse wave can be obtained by dividing the increase of volume after the first pulse wave by the time of the pulse wave. However, as the volume rate during the pulse wave *varies considerably, it is better to measure* the momentary volume rate. For this, the volume vs. time curve of the occlusion plethysmogram is differentiated; the slope of the volume increase, $\Delta V/\Delta t$, is measured at intervals of 0 02 to 0 04 sec and plotted as a function of time The curve obtained represents the volume rate of the arterial *inflow as a function of time*. The *volume rate of the* venous outflow can be also determined, and the last wave of the pulse volume before venous occlusion is recorded The first derivative of this curve with respect to time, as obtained above,

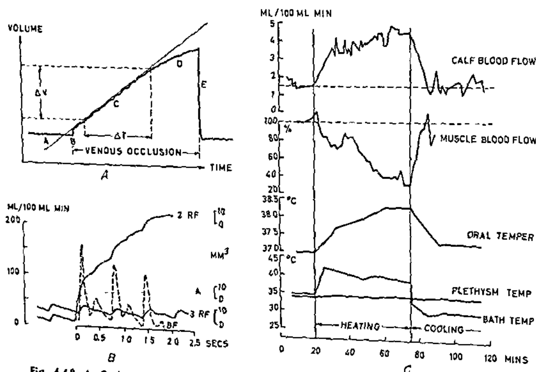


Fig. 4-68. A *Occlusion plethysmogram. A, before occluding the veins, B, artifact during inflation of the cuff; C, linear part of the volume increase; D, nonlinear part of the volume increase; E, end of the occlusion pressure.* B. *Occlusion plethysmogram of the finger 2 RF, volume increase on the right second finger during venous occlusion, A, artifact; BF, tracing of flow in right second finger; 3 RF, pulse volume of the right third finger At right, measurements in mm³; at left, measure of flow in ml/100 ml/min. (From Burch.)* C *Blood flow in the calf (occlusion plethysmogram) and in the calf muscles (heated thermocouple) during warming and cooling of the body in a bath. (From Barcroft et al.)*

gives, according to Eq. (3), the curve of difference between rates of arterial inflow and venous outflow. Subtracting this curve from the curve of rate of arterial inflow, yields, according to Eq. (6), the volume rate of the venous outflow as a function of time.

INFLUENCE OF POSITION AND ERRORS DUE TO REFLEX CHANGES

In plethysmography, especially occlusion plethysmography, various causes of error should be considered. Many disadvantages attributed to plethysmography are based on improper knowledge of how to avoid these errors. As in all methods of studying peripheral blood flow, all disturbing mental and physical influences must be avoided because the vasomotor system is very sensitive to such influences. The room must be quiet and outsiders should be prevented from entering the room and speaking to the patient. Anger, apprehension, and pain should be avoided because they cause vasoconstriction of the skin (Freeman et al, Rothlin and Bluntschli). Special attention should be paid to injections, as they may cause considerable vasomotor reaction through pain or fear Muscle blood flow can also be changed by mental influences, mostly causing an increase in flow (Golenhofen and Hildebrandt). The patient should be comfortable and relaxed. Particularly important is a correct position of the extremity. In order to avoid mechanical displacement within the plethysmograph and fatigue of the patient, the elbow and knee joints should be slightly bent (Barcroft and Swan) The extremity should lie at heart level or slightly above it, so that the veins are collapsed Should the veins be distended, the inflow would cause a substantial increase in pressure.

The amplitude of the pulse at the finger tip increases during elevation and decreases during lowering of the arm, the blood inflow behaves in the opposite way (Turner et al) If plethysmography is performed on full veins, release of venous congestion causes a decrease in volume below the original size, followed by an increase up to normal (Abramson et al., Gaskell and Burton, Allwood) This "afterdrop" can be observed on fingers, toes, hands, feet, and muscular parts, e g , the forearm This phenomenon was first considered as a local reflex. However, according to experiments by Gaskell and by Allwood, it seems to have a mechanical basis. Gaskell believes that venous blood moves from the plethysmograph into the empty veins below the venous cuff. These veins cannot be filled from the proximal side because of their valves. The "afterdrop" appears only when the venous wall is stretched and is proportional to the width of the cuff. Occlusion of the arteries of a hand or a foot can lead to reactive errors in the blood flow of the forearm or calf, respectively. After arresting the blood inflow, one can observe irregular fluctuations in the rate of blood flow of the forearm. However, the tracing returns to the original level in about one minute (Kerslake). Sudden inflation of the arm cuff to 200 mm Hg can cause a diminution of blood flow of about 33 per cent in the contralateral hand. This, however, disappears after 10 to 15 sec (Roddie). Therefore, after an arterial occlusion, one should wait about one minute before proceeding to the venous occlusion.

INFLUENCE OF TEMPERATURE

The first measurements of Hewlett et al. showed that blood flow is considerably influenced by temperature. Therefore, all plethysmographic measurements must be performed at carefully regulated room and plethysmograph temperatures. Except in special cases, the temperature should be kept at a mean level causing neither vasoconstriction nor dilatation. For the forearm, a temperature of the water of 34°C has proved to be optimal (Barcroft and Edholm, 1946). In small segments, as the finger, body temperature is more important than local temperature (Wilkins et al; Goetz, 1943) (Table 4-3).

DIFFERENTIATION OF SKIN AND MUSCLE BLOOD FLOWS

The occlusion plethysmography of the fingers and toes offers practically a pure measurement of skin flow because the flow in other tissues is negligible. Following the skin, the second largest supply is represented by bones,

TABLE 4-3 AVERAGE PLETHYSMOGRAPHIC VALUES OF BLOOD FLOW AS A FUNCTION OF THE LOCAL TEMPERATURE

Local temperatures, °C	*Hand,* ml/100 cm³/min*	*Forearm,† ml/100 cm³/min*
10–15	0 6	0 5
20	1 1	0 5
25	2 1	0.7
30	2 8	1.6
32	4 5	2.3
35	6 8	4.3
37	9.1	5.9
40	.	8 7
45	.	17 6

* According to Freeman

† According to Barcroft and Edholm.

TABLE 4-4. TISSUE CONSTITUENTS OF FOREARMS AND FINGERS, PER CENT

Tissue	Forearm *	Finger, † 1st and 2d phalanges
Muscle.	63.6	
Skin	8.6	50.7
Bone	13.7	17.6
Tendons .	6.1	14.4
Fat, vessels, nerves. . .	8 0	15.9
Nails		1.4

* Cooper et al , 1955.
† *Hensel and Bender.*

where, according to Edholm et al., it is from 0.5 to 1 ml/100 cm³ of bone tissue per minute. *The plethysmograms of hands and feet also reflect mainly changes of the skin blood flow.* More difficult is the differentiation of skin and muscle blood flow in muscular segments of the extremities, like the forearm and the calf. Grant and Pearson thought that, in plethysmography of the forearm, if the hand was excluded from the circulation, the tracing would reveal mainly the blood flow of the skeletal muscles. This assumption was based on the ratio between skin and muscle tissue which, according to measurements of Cooper et al (1955), is 1:7.4 in the forearm; it is also based on experiments with intravenous epinephrine which causes a decrease in the blood flow of the hand and an increase in that of the forearm

One can draw reliable conclusions about the flow of blood in muscle only if the part played by cutaneous flow is minimal. This is the case during an infusion with epinephrine (Barcroft et al , 1955) However, as soon as the cutaneous blood flow changes considerably, the total blood flow in a muscular extremity behaves differently and there may even be a reversal of changes. An example is the flow of blood in an extremity during indirect heating (Fig. 4-68C). According to plethysmographic measurements, the total blood flow in the forearm or calf, while the body is warmed in a bath, increases by about 300 per cent. Comparative measurements by Barcroft et al (1955), using a heated thermocouple, show that blood flow in muscle during indirect heating decreases by 30 to 50 per cent. *Therefore, the chief changes in this case occur in the skin.* In order to eliminate the influence of the skin during occlusion plethysmography, Barcroft et al. (1947) attempted to constrict the skin vessels by electrophoresis with epinephrine. During the first experiments, the cutaneous blood supply was apparently not yet sufficiently blocked because indirect warming still caused a considerable *increase in blood flow in the skin.* Only with strong electrophoresis (epinephrine 1/2000, 20 ma, 10 to 20 min duration) is it possible to obtain a satisfactory block of blood flow in the skin, as revealed by lack of increased blood flow after releasing arterial occlusion and warming the arm, as well as by failure to bleed when cut (Cooper et al., 1955). *During rest and at different room temperatures, cutaneous blood flow varies in the same way as muscle flow.* With greater total blood flow, the blood flows in both muscle and skin increase, however, the values are different (Table 4-5).

The technique of occlusion plethysmography with epinephrine electrophoresis has the advantage of making absolute measurements of blood flow in skin and muscle possible, if errors due to other tissues are not considered. A disadvantage is that it is impossible to perform simultaneous measurements of the cutaneous and muscle blood flow on the same extremity Besides, it is possible that a complete elimination of the cutaneous blood flow leads, either hemodynamically or in a reflex way, to changes in muscle blood flow. As Cooper et al. (1955) have remarked, it is not certain that skin blood supply is entirely eliminated. The circu-

TABLE 4-5 TOTAL AND FRACTIONAL BLOOD FLOW IN THE FOREARM

Total flow, ml/100 cm³ forearm/min	Flow in skin, per cent		Flow in muscle, per cent	
	Average	Range	Average	Range
0–3 *	19	0–38	81	62–100
3–6	27 5	0–47	72.5	53–100
6 † and over	50 5	32 5–80	49 5	20–67 5

* At optimum temperature, 34°C, total flow is 3 1, cutaneous flow 3 0, and muscular flow 3 0 ml/100 cm³ tissue per minute
† In various conditions, cutaneous flow ranges from zero to 70 5 ml/100 cm³ skin per minute, muscular flow from 1 8 to 9 6 ml/100 cm³ muscle per minute
SOURCE: After Cooper et al

lation can also be influenced by absorption of epinephrine.

SPONTANEOUS WAVES IN THE PLETHYSMOGRAM

The volume of an extremity changes continuously, even in the absence of external stimuli. The more distally the measurement is made, the more obvious the volume changes become. These fluctuations in volume are particularly marked in plethysmography of the finger tips. Only the terminal segments of organs are suitable for exact wave analysis because the tips consist of more homogenous and uniformly reacting tissues. The following waves can be distinguished.

1. *Pulse waves* (volume pulse). The amplitude of the pulse waves increases in proportion to the rate of blood flow (Burton, 1939, Goetz, 1943, Hertzman et al., 1945). (For details, see below.)

2. *Respiratory waves.* The purely mechanical displacements of the extremity due to respiration should be excluded.

3. *Vasomotor waves.* The genesis of the various vasomotor waves is not yet satisfactorily solved. Probably these waves are correlated with pressure and temperature regulation. The waves are larger at indifferent temperatures, not causing either vasoconstriction or vasodilatation. The most obvious have the following intervals. 10 to 20 sec (*alpha waves*—Burch et al., Matthes, 1951, Cerletti), 1 to 2 min (*beta waves*), up to 15 min (*gamma waves*). Burch et al found in the finger tips the average volume amplitudes shown in Table 4-6.

FUNCTIONAL TESTS

Besides obtaining plethysmographic values at rest, it is important to perform plethysmography under various functional conditions and stresses of the circulation. All physiological and pharmacological stimuli which act on the vessels can be used. From a clinical standpoint, it is interesting to measure the maximum possible dilatation of the vessels, since this may be the decisive factor in making therapeutic success possible. Functional tests in plethysmography correspond essentially to methods of vascular examination. However, they have the advantage of giving quantitative results.

TABLE 4-6 VOLUME AMPLITUDE OF THE VARIOUS WAVES IN THE FINGER TIPS

	Volume, mm^3
Pulse waves	7
Respiratory waves	2
Alpha waves (10 sec)	14 5
Beta waves (1 min)	30
Gamma waves (15 min)	150
Total volume of finger tips	5,000
Blood volume of the finger tips	800

SOURCE: Burch et al.

Thermal Stimuli. The degree of dilatation of human blood vessels, especially of finger tips, ears, and toes, is determined first of all by the requirements of the thermoregulation while the nutritional function is of secondary importance. Except at very low temperatures, the blood flow in the skin is considerably higher than is considered necessary from the standpoint of nutrition. Heat stimuli, local and reflex, are widely used for studying the functional condition of the small blood vessels in the extremities. The most effective stimuli are obtained by warming or cooling the entire body. Standardized warming can be performed in a warm bath or in a hot box. In the finger, Burton (1939) obtained values of 0 5 to 1 ml/100 cm^3/min during vasoconstriction, up to 90 ml/100 cm^3/min during extreme vasodilatation. This corresponds to a cutaneous blood flow of 180 ml/100 cm^3 of skin per minute. Goetz found a maximum value in the fingers of 93 ml/100 cm^3/min (1943), in the toes, up to 90 ml/100 cm^3/min (1946). Partial warming of the body, as by immersion of an extremity into hot water, is a useful test for reflex vasodilatation (Cooper and Kerslake). Barcroft and Hamilton immersed both feet of patients in water at 45°C and recorded the dermal blood flow for an hour. The ratio of the cutaneous blood flow observed before, to that observed after warming (*heat ratio*) is a valuable test for sympathetic vasomotor activity. They obtained, in the normal hand, an average heat ratio of 9.5; following sympathectomy the ratio was 1.0. It is practical to perform tests with local warming only with plethysmographs filled with water. During maximum vasodilatation, values of 34 ml/100 cm^3/min can be obtained for the hand; of 17 1 ml/100 cm^3/min, for the foot (Kunkel et al.). The volume amplitude of the finger

or toe plethysmogram offers a useful measure for the degree of reflex changes of blood flow becaus[illegible] f the pulse is proportional to the [illegible] 1943; [illegible] such as that caused by application of [illegible] the *contralateral* extremity, cause a reflex vasoconstriction of the skin vessels. Here the finger plethysmogram can offer valuable information about an existing tendency of the small arteries to spasms due to cold (Kappert, 1956).

Reactive Hyperemia. The degree of reactive hyperemia following arterial occlusion is also an extremely useful test of the capacity of dilatation of the vessels. This test may reveal disturbances which cannot be demonstrated during resting conditions. The amplitude of the volume pulse (Kappert, 1956), as well as an occlusion plethysmogram can be determined. *Freeman found on the hand that,* after 10 min of arterial occlusion, there was a tenfold increase in blood flow. On the calf, the flow, after 3 min of *arterial arrest,* was found to have increased 5.8 *times (Hensel* and Bock); after longer occlusion, it can increase up to 10 times or more (Hess, 1956). By using *special equipment, it is possible to* perform occlusion *plethysmography of the calf* during exertion. The flow then increases up to 40 ml/100 cm³ tissue/min (Barcroft and Dornhorst).

Sympathetic Block. The elimination of the *sympathetic tonus of the vessels* by sympathectomy or sympathetic block causes a considerable increase in the cutaneous blood flow of the *extremity, while* muscle blood flow increases *only very little. Barcroft* and Walker and Lynn and Barcroft obtained an average increase *in blood flow* from 5.2 to 39.1 ml/100 cm³ of tissue per minute *from* 1 to 2 days after sympathectomy. In the *foot, an average increase of from* 2.1 to 20.0 ml/100 cm³/min was found. Several weeks later, the flow was only slightly above the original level. *In the* muscle, after blocking the deep nerves, there was only about a *doubling* of the blood flow (Barcroft and Swan). This *result of occlusion* plethysmography was confirmed by direct measurements with a *heated* thermocouple (Golenhofen and Hildebrandt).

Vasoactive Drugs. In testing the effect of vasoactive drugs, one should first distinguish the *effect* obtained upon blood flow in skin and muscles, respectively. Certain substances, like the adrenergic blocking agents, the ganglionic *blocking agents* and certain *derivatives of nicotinic acid,* cause mainly hyperemia of the skin (Hensel et al., 1955). Therefore, they can be used for testing the distal parts of the extremities. *In testing the vasoactive drugs by occlusion plethysmography of the calf or fore*arm, one is not sure whether he is testing their effects upon the vessels of the skin or upon those of the muscles. *Therefore, it is always advisable to register* the blood flow *of the most* distal parts of the body. Ten milligrams of ATP intraarterially cause a maximum dilatation of the vessels of muscle (Hess). An *intraarterial insufflation of oxygen also* leads to a considerable increase of the muscle blood flow (Duff et al., Hess and Bartelmess; Golenhofen et al.).

CLINICAL APPLICATIONS

In the past, plethysmography was considered a procedure which, because *of its technical difficulty, was limited to special laboratories.* Then plethysmography was used more and more frequently in clinical diagnosis, and it proved to be a valuable addition to other *angiological examinations. For clinical* purposes, first of all one has to consider the simple recording of volume on fingers and toes. *Occlusion* plethysmography, even though more difficult, has *been already* used in several clinical examinations. The following clinical applications of plethysmography should be kept *in mind* (Kappert, 1956).

Measurement of Peripheral Volume Pulse. The form of the peripheral *volume pulse* of fingers and toes is studied. As long as the heart and the tissues *do not* show severe alterations, definite conclusions can be *drawn* from this *study in regard to the arterial system (Matthes* et al., Lund, Kappert, Volker et al.) In order to eliminate vasospasm, *the body* is warmed in order to promote maximal vasodilatation. The *propagation time* is then studied, *namely, the* time interval *between the* R wave of the electrocardiogram and the *rise of the* pulse. *Further, the inclination time* (Lund) should be measured (Fig. 4-69). A tangent to the steepest part of the pulse curve *is* made and the *crossing* of the base line, and the *top* line is observed. The *time* between those two points

lation can also be influenced by absorption of epinephrine.

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hand or foot by a factor of 10, can indicate whether sympathectomy is the treatment of choice. The effect of other therapeutic measures upon the circulation in skin can also be tested quantitatively.

Occlusion plethysmography of calf and forearm, *while the subject is at rest*, frequently fails to give reliable information about the disturbance of circulation in the muscles. In more advanced obliterative processes, the circulatory disturbance of the muscles is easily observed. However, the diagnosis of such cases is easy. Hess (1956) only exceptionally found resting values below 1.0 ml/100 cm³/min in patients with vascular disorders. On the other hand, he frequently found values above the normal value of 3.5 ml/100 cm³/min. Evidently, a great number of collaterals compensate or even overcompensate the circulatory disturbance. Circulatory disturbances become evident only after maximal dilatation has been produced by reactive hyperemia. Normally, the circulation of the calf can increase up to 30 ml/100 cm³/min, while in patients with vascular disorders, only much smaller values are obtained (Hess, 1956).

THE CAPILLARY CIRCULATION

THE HUMAN CONJUNCTIVAL CAPILLARY BED

Introduction

With the demonstration that the capillary bed of certain laboratory animals could be prepared suitably for visualization under the microscope, knowledge concerning the most peripheral vascular phenomena was obtained in a variety of laboratory-induced pathological states (Zweifach, Knisely; Lee, 1947; Chambers). Although the operative procedures that are necessary for the laboratory examination make it difficult to repeat these techniques in

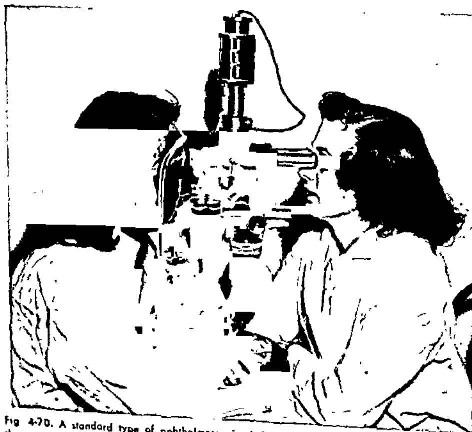


Fig 4-70. A standard type of ophthalmoscopic slit-lamp microscope for examining patients in the sitting position.

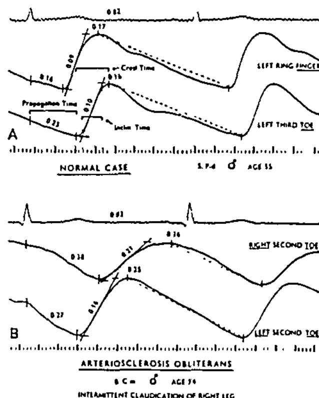


Fig. 4-69. Analysis of volume pulse. Time 0.1 and 0.02 sec. A. Normal subject. electrocardiogram and plethysmogram of finger and toe. B. Patient with arteriosclerosis obliterans of both legs; ECG and plethysmograms of toes on both sides. The arterial obstruction is more marked on the right. (*From Lund.*)

is the inclination time, which measures the steepness of rise of the pulse. The *crest time* (Dillon et al.) is the time between the rise and the peak of the pulse. According to Lund it is less reliable as it depends not only upon the steepness of ascent but also upon the shape of the peak The descending limb of the pulse normally has a slight upward concavity and a distinct dicrotism. Prolonged "propagation" and "inclination" times, a convex descending limb, and the absence of the dicrotic wave, are evidence of arterial obstruction. In many cases, the plethysmograph reveals definite abnormalities of circulation which are not as yet shown by oscillometry (Lund) Plethysmography is particularly indicated in patients with *organic arterial diseases*. In *coarctation of the aorta,* Lund found typical changes, like prolongation of the propagation time and inclination time and abnormal course of the descending limb. All these changes reverted to normal after surgery.

Study of the vasomotor changes of the peripheral pulse and the modifications occurring during functional tests (warmth, cold, reactive hyperemia, sympathetic block, drugs) offers valuable information about the functional and organic components of a disturbance of circulation. This can be of value in Raynaud's disease, thromboangiitis and arteriosclerosis obliterans, etc. It also may supply valuable data, to aid the decision whether to advise sympathectomy or other therapeutic procedures. As the spontaneous vasomotor changes occur simultaneously in symmetrical parts of the body, unilateral weakening of the latter is an important diagnostic sign. Volker described a paradoxical vasomotor rhythm on the diseased side in thromboangiitis obliterans. The phenomena of spasm in Raynaud's disease can be well recognized through diminution or disappearance of the peripheral volume pulse

Measurement of Circulation by Occlusion Plethysmography. Quantitative measurement of circulation by occlusion plethysmography offers exact information about circulation disturbances. Measurements on hands, fingers, feet, and toes, supply information about the rate of blood circulation in the skin. As the circulation is larger than necessary for the nutritional needs of the skin, the clinical symptoms appear only when there is already a serious disturbance. On the other hand, the disturbance can be recognized by plethysmography before the symptoms appear. According to Kunkel et al., arteriosclerosis and thromboangiitis obliterans can impair the circulation by 50 per cent without causing any pathological symptoms. Only after a reduction to 30 per cent of normal or 5 ml/100 cm^3 of tissue per minute do the clinical symptoms and trophic changes appear. Occlusion plethysmography reveals the disturbance much earlier than skin temperature measurements. Goetz (1946) found in patients with vascular disorders a 60 per cent impairment of the circulation of the toes while the skin temperature was still normal Therefore, one should not wait for alterations in skin temperature as evidence of arterial deficiency, otherwise, early diagnosis would be impossible. Together with indirect warming, occlusion plethysmography of fingers, toes, hands, and feet gives quantitative information about sympathetic tonus and the functional capacity for dilatation of the vessels The effect of a sympathetic block, which normally increases the circulation of the

the total effective tissue blood supply consists of counting the number of patent capillary vessels containing blood per unit of tissue. The number of open capillaries generally reflects the state of arteriolar widening

Reactivity to Pharmacological Agents. The responsiveness of arterioles and precapillary sphincters of laboratory animals to *epinephrine* and other agents has been used as a criterion of peripheral vascular reactivity. This end point can also be obtained directly in the human capillary bed. With the patient in a sitting position and the head and neck extended backward so that the eye surfaces are generally horizontal, measured amounts of solutions of *epinephrine, norepinephrine, histamine,* or other agents, can be applied to the conjunctiva. By observing specific arterioles and capillary beds prior and subsequent to the conjunctival instillation of such agents, resultant vascular phenomena can be observed. For example, it is possible to determine which concentration of *epinephrine* produces a *threshold* (*i e, just noticeable*) closure, either of the precapillary regions or of the terminal arterioles. Subsequent to the use of such vasodilator drugs as *histamine*, a similar concentration of such drugs for *threshold vessel dilatation*, can be found. Although the threshold doses of *epinephrine* and *norepinephrine* in human beings have been shown to be considerably higher than those of animals, the "graded" nature of reactivity to such vasoconstrictor stimulation in the capillary bed has been found to be true both in the laboratory and in the clinic It is of interest that drugs found to be directly vasoconstricting or vasodilating in the mesentery of animals have proved to have similar action in the capillary vessels of the human conjunctiva.

Effect of Physical Agents. The naturally exposed location of the conjunctival vessels allows them to be stimulated by *heat, cold,* and also *direct trauma*, applied either through the closed lid as massage, or directly to the anesthetized conjunctiva as, for example, with a camel's-hair brush. In most subjects, the application of an ice pack to the closed lid for 2 min will be followed by prominent vasoconstriction of the arterioles and a closure of the precapillary regions. *Heat, applied* generally as a hot pack in the same manner, will generally be followed by a noteworthy vasodila-

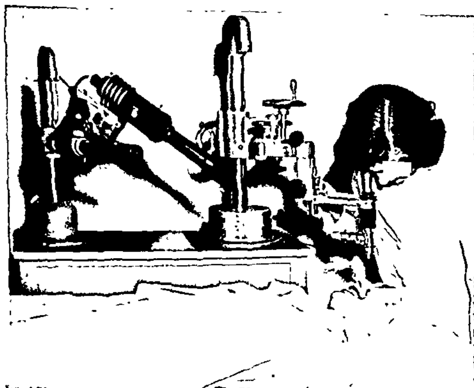


Fig. 4-72. Vertical microscope with accessory illumination for examining patients who are supine.



Fig. 4-71. The capillary bed in a normal conjunctiva. A, arteriole; C, capillary, V, collecting venule. (×240.)

human beings, the capillary bed of the naturally exposed human conjunctiva is of sufficient area and accessibility for examination at magnifications of relatively high power without any necessity for extensive procedures or anesthesia It is easy to obtain information on the anatomy and topography of the capillary vessels in this region, with experience, studies are possible regarding abnormalities in velocity of flow and spontaneous vasomotion, and the vasoconstrictor or dilator responses to various directly applied drugs can be photomicrographed and reviewed without difficulty The techniques have made it possible to collect data concerning the capillary vascular abnormalities in several different cardiovascular states (Lee et al., 1955; Schulman et al.; Bloch)

The Apparatus. For routine studies, the standard type of *slit-lamp apparatus* can be readily adapted for examination of the conjunctival capillary bed The illumination is adequate for visualization, and extensive processing of the negative permits photomicrographs A limiting factor that determines the degree of magnification at which somewhat prolonged observation can be made is the habit of the human eyeball of constantly shifting the projection of the image upon the retina by means of rapid and asynchronous automatic motions. Therefore, when the vessels are viewed at a magnification significantly greater than 50 power, these movements of the eyeball will shift capillary vessels completely out of the field and make continuous study impossible. Thus, for most purposes, magnifications of 50 power represent nearly the upper limit of magnification that can be used with ease Figures 4-70 and 4-72 show standard types of slit-lamp microscope apparatus; Fig. 4-71 illustrates certain peripheral vascular components in the conjunctiva of a person without known disease. The vessels are labeled to indicate arterioles, capillaries, and venules. For observations on patients who are conscious and able to sit erect without difficulty, the erect position is greatly to be preferred. When the patients are lying supine and magnification of the vessels is carried out at 50 power, the horizontal motions imparted to the body by cardiac systole produce to and fro movement of the conjunctiva and vessels and thereby greatly encumber continuous study. When one desires information about capillary phenomena in patients who are unconscious or so critically ill that sitting erect is not feasible, it is possible to study the capillary bed in the conjunctiva with the subject in the supine position (Fig. 4-72). Magnification, however, should be limited to not more than 20 to 30 power at most. This reduces the apparent degree of motion of the field and, with a suitably intense light source, allows photomicrographs for subsequent review. The light sources used have been several; any low-voltage, high-intensity light source will prove adequate providing that it is cooled by suitable means, so that it does not warm the tissue and thereby induce vascular dilatation.

Determination of Tissue Blood Supply. With photomicrographs of the human capillary bed projected against a large screen, the diameter of arterioles and venules can be measured, and the state of relative vasoconstriction or dilatation determined, by comparing the values found with known normal values and correcting for the degree of total magnification By focusing carefully on selected arterioles or venules or the straighter capillaries during observations and using a calibrated ocular micrometer (Fig. 4-73) the speed of passage of single red cells or red-cell sections of the blood column can be measured with a fast stop watch The method can be used to indicate alterations in the velocity of flow, secondary either to profound dilatation or to narrowing of the vessels observed A third technique for determining

approximately 10 to 20 microns on the average. Their total length is variable but usually is at least 200 to 300 microns. The so-called *arteriolar* or *efferent* arm is prominently less wide than the loop segment which returns blood to the venous system, and is the portion displaying the most apparent vascular narrowing in response to oral and parenteral administration of vasoconstrictor materials. At the *cap*, or most distal part, of this vascular structure, the vessel sometimes balloons out quite widely, particularly in rheumatic and certain other illnesses. Blood flow is usually quite rapid comparing favorably with that of arterioles in the conjunctiva. Because of the overlying epidermis, it is quite difficult to study the effects of directly applied pharmacological agents on these vessels. Lewis' method of blistering off the epithelium, allows them to be reached by permeable agents in solution; however, there is no question but that the blistering process interferes with vascular responses and possibly produces an abnormal vascular picture. For this reason, the study of nail-fold capillaries and vessels in the subepithelial areas of other body parts (see below) is best restricted to observing the numbers of patent vessels, their diameters, and the general appearance and velocity of blood flow under normal circumstances and when agents are administered orally or parenterally to produce over-all vascular reactions.

VESSELS ON THE INNER ASPECT OF THE LOWER LIP

The squamous epithelium covering the inner aspect of the lips is particularly thin and transparent, it permits the underlying arterioles, capillaries, and venules to be seen in a typical vascular network more frequently than is possible in the nail bed.

With the subject's head resting in a chin and forehead support similar to that illustrated for use with the slit-lamp microscope, the lower lip is extended out over a rigidly supported transparent glass or plastic plate and held in position with spring-type clips of the kind customarily used to hold microscope slides on the stage. The usual type of monocular compound microscope with magnification of 10 to 50 power is used in the same manner as in examination of the nail fold, employing direct reflected illumination. Those areas of the lips lateral to the line of the nose are best used, for it is difficult if not impossible to arrange the microscope to examine the lip surfaces directly in the midline.

Although a complete vascular network is more frequently encountered here than in certain other areas, the overlying epithelium imposes the same restrictions to the study of direct application of pharmacological agents that are encountered in the nail-fold technique. However, with specially selected vessels, the effect of direct mechanical trauma, as well as that of heat and cold, can readily be observed. With an especially strong and well-cooled light source, this area can also be transilluminated to some extent in order to improve visualization of the vessel wall. The thickness of the lip will vary in individuals, however, and transillumination frequently is not possible

THE EXTERNAL EAR

The thinness of the pinna and its flexibility make it possible to examine the vascular changes over the external ear with an ease at least equal to if not greater than that of examining the lip. Moreover, because of the lack of dense subcutaneous tissues, comparatively speaking, a combination of lighting methods using both transillumination and direct illumination is readily possible. Here, complete vascular networks can be seen with some clarity, particularly if a clearing agent is applied to the surfaces in the same manner as was recommended for the nail-fold method. Again, the presence of overlying epidermis interferes with studies involving direct application of drugs, but does not interfere significantly with examination of the effects of mechanical trauma, direct thermal stimulation, or systemically administered agents.

The ear areas are best examined with the use of a lucite rod technique and direct transillumination, in a manner comparable to that developed by Knisely for the study of organ circulation in small laboratory mammals It is of interest that study of cutaneous and subcutaneous vessels of the ear and other areas is much easier in individuals who are redheaded or naturally blond. Although this is perhaps partly due to the absence or relative scarcity of pigmentation, the subcutaneous tissues of such individuals seem otherwise to be capable of illumination or transillumination with greater clarity.



Fig. 4-73. Ocular micrometer placed alongside and parallel to a medium-sized venule (arrow) so that the passage of erythrocytes from point 2 to point 5 can be timed during experimental procedures.

tation of all vascular elements The threshold of susceptibility to such stimuli can readily be established by noting the temperature of the lid of the conjunctiva with suitable thermoelectrical means and the duration of the exposure necessary to induce changes

Comment. As with any relatively new technique, experience and familiarity with the procedure of studying the human capillary bed are particularly essential. It is at first difficult, especially if the subject is not completely cooperative, to follow the blood flow rates and the changes in content of a single capillary of the conjunctival bed Speed of passage of red cells in arterioles will at first make it difficult to select specific cells for the timing of flow velocity. As experience is gained, however, the ease and assurance with which observations can be made and objective criteria, particularly with regard to threshold responsiveness to drugs and flow velocities in the various elements, will be found to check very closely, and quantitative data with determination of standard errors and so forth, will be easily obtained. At all times, in so far as it is possible, visual observations should be documented with clear photomicrographs. The microscope camera, used with facility, is an important part of human biomicroscopic technique.

NAIL-FOLD CAPILLARIES

Observations on small blood vessels in other exposed surface areas of the body have been carried out for many years. The "capillary" vessels in the nail fold were first studied in detail in 1912 (Lombard), with subsequent expansion of this method and inclusion of other areas as well in 1927 (Lewis). In the nail-fold region, the epidermis overlying the nail-bed is thin, and a drop of mineral oil or other clearing agent will reduce the reflected light and permit visualization of subepithelial vascular structures.

A standard compound microscope with magnifications of from 10 to 100 power is satisfactory for all skin areas. The light source should be intense (but of low voltage and preferably with light beam filtered through water) and should be directed towards the area studied at an angle of from 45 to 60°. For optimal support of the arm, hand, and finger, a soft sand bag of suitable size is arranged to hold the hand and fingers in a position directly beneath the objective lens (Fig 4-74) completely free of muscular effort or strain on the part of the subject.

The nail-fold vessels are *capillary loops,* of hairpin shape, that range in diameter from

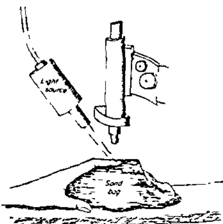


Fig. 4-74. Diagrammatic illustration of arrangements of hand, light source, and microscope for optimum visualization of nail-fold vessels.

4

Ballistocardiography

The Ballistocardiogram

ALDO N. CORBASCIO AND ISAAC STARR

Origin of the Ballistic Movements of the Body

JOHN L. NICKERSON

THE BALLISTOCARDIOGRAM

HISTORICAL BACKGROUND

The observation that the action of the heart may produce rhythmic oscillations of the body is certainly very old. Clinicians have been aware of it for centuries, that some clinical conditions accentuated this readily observable phenomenon of bodily pulsation must have been evident to the physician in charge of a famous case of aortic insufficiency, the French poet Alfred de Musset, this clinician observed that the head and the neck of his patient would show a slight but distinct jerk backward with each beat of the heart. The "de Musset sign" is still part of the clinical terminology of this disease. Parry, an English physician, described movements of the body with each beat of the heart in a case of hyperthyroidism reported in 1825.

The first record of these movements was made by Gordon (1877) who employed a bed suspended from the ceiling, a set of levers, and a smoked drum. Gordon's idea was derived from the casual observation that, while he was standing still on spring scales, the pointer would oscillate synchronously with the beat of his heart. Landois (1879) described a simple instrument by which he found that the record of a patient with aortic insufficiency exceeded in amplitude the records of normal subjects, an observation that holds true to this day.

Unaware of these attempts, Henderson (1905) tackled the problem anew by building a suspended table on which the subject lay. The table was free to move in the longitudinal direction only, and its motion was magnified by levers and recorded on a kymograph. Satterthwaite once more observed that the pointer of the scales in his office would move in time to the beating of the hearts of his patients and, by increasing the length of the pointer and placing the tip on a kymograph, he secured some fairly good ballistocardiograms. In 1928 Angenheister published records of the impacts of the heart by placing a seismograph on a rigid table on which the subject lay. In 1935 Abramson described a ballistic chair and published a few records but did not continue his experiments.

The first instrument well-adapted to routine use in the clinic, a high-frequency table with optical magnification and photographic recording, was described by Starr and coworkers (1939). This instrument was called the "ballistocardiograph" (from the Greek βάλλω = I throw, καρδία = the heart, γράφω = I write), a term which implicitly described its functions and scope. At that time, the terminology employed today and the physiological foundations of the ballistic theory were laid, by calling attention to the relationship between the ballistocardiogram and the forces portrayed by the cardiac ejection curve. An instrument for the vertical position was constructed soon after, but it proved less suited to routine clinical work than the table type.

In 1948 Brown and Pearson applied a new system of electrical pick-up and recording to a high-frequency table. In 1949 Nickerson constructed a free-swinging, low-frequency, critically damped table. In 1949 Dock and Taubman proposed a method which was a great simplification. They recorded the motion of a rigid bar placed across

THE SCROTAL VESSELS

The thinness and abundant blood supply of the scrotum would seem to make it particularly suitable for examination of its capillary vasculature with transillumination. Preliminary studies in this area, however, have indicated that the topography of this peripheral circulation is such that observation (particularly of the arteriolar tree) is very difficult. Many of the arterioles in this region are arranged "end on" or perpendicular to the skin surface; these arise directly from the subpapillary plexus to branch over the skin in small capillary-like vessels that conflow to form venules. Many of them then turn and leave these subepithelial levels to descend to subcutaneous connective tissue, and are not readily visualized. However, with careful search, suitable regions may be found where small arterioles and capillaries can be seen with some clarity, particularly if both transillumination and direct lighting techniques are employed together. In this way, at least certain observations are possible on circulatory changes in the small subcutaneous vessels of this region, to compare with those noted in the nail fold, conjunctiva, and other areas.

GENERAL CONCLUSIONS

Methods are outlined for observing the circulation in the peripheral vessels of the superficial body parts of man. Because of the thinness, permeability, and transparency of the supravascular epithelial tissue, and because of the white sclera that lies beneath the vessels and serves as a reflecting surface for illumination, more can be learned concerning peripheral vascular reactions to pharmacological agents and to thermal stimuli in the vessels of the conjunctiva. Small vessels in other regions of the body, however, are accessible for examination and, with the special methods of illumination which have been outlined, much can be learned concerning the responses of peripheral circulation in man to a variety of localized direct stimuli and to the administration of oral or parenteral medications. It should be emphasized that any phenomena noted in the vessels of these regions represent changes in parts of the peripheral circulation that are often quite specialized, such reactions do not necessarily reflect vascular responses that occur elsewhere under the same circumstances.

4

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more complicated and the apparatus more fragile than in the older type, and calibration is not so simple an operation Some authors have interested themselves in recording the *displacement* and *velocity of such tables, thus securing records which* are the first and second integrals of the more usual force records This system minimizes the movement between subject and table and theoretically is the most nearly perfect system yet devised. Normal records secured by this method are shown diagrammatically in Fig 4-76, and examples are *given in Fig 4-77.*

Direct body instruments record the movement of a bar placed on the subject's *shins relative to* the immovable surface on which he lies This simplification results in a great saving of expense, but as scientific instruments the shin-bar methods are not in the same class as the tables. Recently several improvements have been made, bars have been made lighter, and their attachment to the shins has been improved. In the original Dock apparatus, *velocity* was picked up and it was planned to integrate the record to one of displace*ment by means of a condenser. But the condenser*

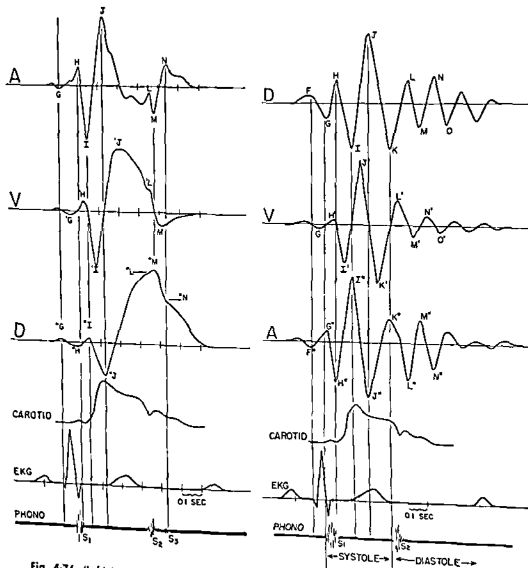


Fig 4-76 (Left) Ballistocardiograms from an ultralow-frequency instrument (the mercury bed) to show the time relations of the records to one another and to the pulse, electrocardiogram, and heart sounds. A, the record when acceleration is recorded (the force record). V, the record when velocity is recorded. D, the record when displacement is recorded. (Right) Direct body, or shin-bar, ballistocardiograms showing time relations when displacement, D, velocity, V, and acceleration, A, are picked up (From Scarborough and Talbot. Circulation. 1956. By permission of the publisher)

the subject's shins by means of a coil-and-magnet transducer, a method picking up velocity which may be integrated to give a record of displacement.

Interest in other dimensions than that from head to foot awoke early. Braunstein and coworkers (1950) described a two-dimensional, high-frequency ballistocardiograph. Scarborough and Talbot (1953) introduced a high-frequency instrument constructed as a turntable which gave records in the three planes of the body. A torsion instrument recording rotatory movements has also been constructed.

By this time the interest of physicists had been aroused. Von Wittern and also Burger proposed a new method of securing force ballistocardiograms by recording the acceleration of low-frequency tables, a design which minimized the error caused by movement between table and subject. The "mercury bed" of Scarborough and Talbot, a completely aperiodic system, belongs to this group of instruments. For use with such systems, Elliot and Packard (1954) employed an ingenious and simple capillary accelerometer.

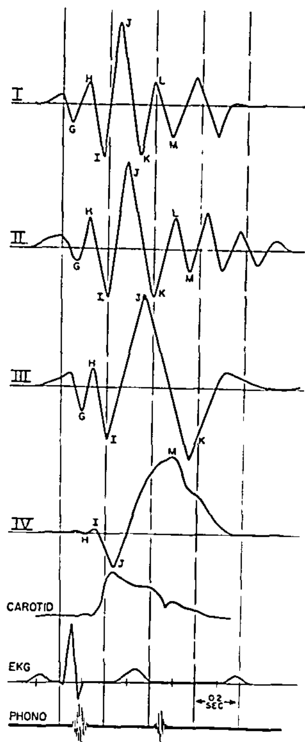


Fig. 4-75. Reproduction of *displacement* records from different types of ballistocardiograms to show their time relations with one another and with electrocardiogram, carotid pulse, and heart sounds. I. High-frequency. II. Direct body III. Low-frequency. IV. Ultralow-frequency. *(From Scarborough and Talbot. Circulation. 1956 By permission of the publisher.)*

PHYSICAL BACKGROUND

The physical background of the field has been extensively studied, but it requires specialized knowledge and a vocabulary beyond that of most practicing doctors. Those desiring more knowledge of such aspects of the field could consult the original publications of von Wittern, Burger, Talbot, and Rappaport. An excellent presentation will be found in the Technical Appendix written by Scarborough and Talbot under the auspices of a committee of the American Heart Association.

INSTRUMENTS

The instruments widely used at present fall into three classes. In *high-frequency tables* the movement is resisted by a strong spring so that it is at a minimum Such tables have the advantage of being rugged and durable, and the electric circuits needed in them for amplification and recording are simple When *displacement* is recorded, they give a record of force which is readily calibrated by means of a weight and pulley system that displaces the base line when a known force is applied. The disadvantage of the high-frequency table lies in the difficulty of preventing motion between subject and table. This may be minimized by tight attachment, but probably not completely overcome. The normal record of the older type of these instruments is given diagramatically in Fig. 4-75

Low-frequency tables are hung from long suspension cords and they are free to move in the longitudinal direction In some models, damping is added, but results are better without it. These tables yield records of force when *acceleration* is picked up, but the electrical circuits required are

demonstrated *in cadaver experiments* in which systole was simulated (Starr et al., 1954). The *movement* of the body transmitted to a table can be calibrated against a known force, thus enabling one to evaluate with fair approximation the relative magnitude of those forces of the cardiac contraction which cause the ballistocardiogram

As, *under normal circumstances, when the heart contracts with great force, the stroke volume is large and vice versa, there have been several attempts to estimate stroke volume from ballistocardiograms.* When the subjects are normal such methods work quite well but, under *abnormal conditions, the heart appears able to conserve its force while maintaining* its output and the ballistocardiographic stroke-volume methods proposed to date are of little use in routine clinical work *While the amplitude of the ballistocardiogram tells one of the strength of the heart's contraction, this is only indirectly related to its output.*

TAKING AND READING THE RECORD

The subject should be allowed to lie on the table 15 min in order to permit his circulation to attain the resting state before taking the record. As digestion increases record amplitude, records should not be taken within 2 hr after a meal A simultaneous record of pulse or electrocardiogram is of help in interpreting some abnormal records

The beginner in this field must be started with a warning about artifacts, for any movement made by the patient produces impacts which are recorded With a little practice these are easily identified. *The rule is* that nothing not regularly repeated is worthy of attention. However, the procession of identical complexes so characteristic of the ECG is never seen in the ballistocardiogram unless the breath is held Since the most valuable records are secured when the subject is breathing at normal depth and rate, when one wishes to rule out artifacts, one compares similar complexes in corresponding parts of the respiratory cycle

THE NORMAL RECORD

The great similarity of the records secured in all healthy young adults is a striking feature of the field. Drawings of such normal records are illustrated in Figs 4-75 and 4-76 and the letters applied by a committee of the American Heart Association to designate the waves are shown In normal records, the position of systole can be identified at a glance. The respiratory variations are always seen, the record increasing in amplitude *during inspiration* and decreasing during expiration Figure 4-77 gives *examples.*

In some healthy subjects, modern methods show a notching which was seen neither in the older table records nor in direct body records. Figure 4-77 gives an example This is to be attributed to normal asynchronism of the forces from the two sides of the heart, ejection from the right side often preceding that from the left, because pulmonary diastolic pressure is so much lower than aortic

Studies defining the normal limits of amplitude for high-frequency table records are available, but as these differ somewhat with the type of apparatus used, workers in this field must assure themselves that their results conform to those from which the standards were obtained before employing them.

THE WAVES OF THE NORMAL BALLISTOCARDIOGRAM

The force ballistocardiogram is the record most commonly taken and the descriptions which follow will be confined to this type of record The main components of the ballistic complexes constitute a set of waves of different amplitude and duration, distinguished by a corresponding letter of the alphabet These are shown in Fig. 4-75 The first is called *G*. It is a negative deflection of small amplitude seen in almost all records Its meaning is undefined. The second wave in the complex is *H*, which usually falls in step with the QRS complex of the ECG, and is a small headward wave that in some abnormal conditions may be much larger. *It certainly has an atrial component, for the* H wave is usually absent in atrial fibrillation and in cases of complete AV block when the atria contract at an abnormal time However, *some cases of atrial fibrillation* show a good H wave and this component has been variously related to movements of the heart during the isometric phase *of systole*, to movement of blood within the heart *due to* a weak spot in *its* wall, or to regurgitation into the veins The 3d and 4th waves, *I* and *J*, are the most *conspicuous* waves of the whole complex The I wave is a movement of the *body, toward the*

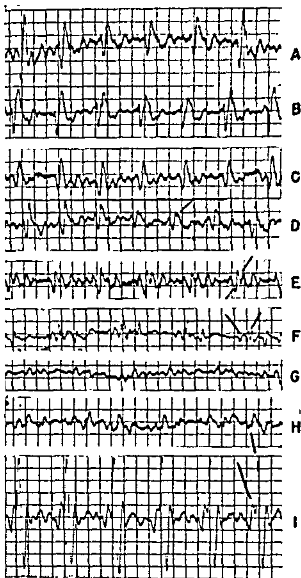


Fig. 4-77. Normal and abnormal ballistocardiograms, some taken with the subject on a high-frequency table recording displacement, and others on an ultralow-frequency table recording acceleration Both sets were calibrated so that a force of 280 Gm displaced the record 1 cm The reduction is to one-half of the original size. The slanting lines point to features of interest *A*, record from a high-frequency table (with displacement recorded) of A N, a healthy young man, age 27 The form and amplitude are normal. Breathing is somewhat exaggerated and the record arches more than is usual in healthy subjects when they are well relaxed *B*, record (from an ultralow-frequency table with acceleration recorded) of the same subject as in (A). Note the great similarity between ballistocardiograms taken with the two types of instruments. *C*, record (from a high-frequency table of G N., a healthy woman, age 28. A normal record. *D*, record (from an ultralow-frequency table) of G. N Note that the ultralow-frequency record shows notching on certain J-wave peaks not shown by the high-frequency record, and K tends to be a little deeper in the high-frequency record. *E*, high-frequency record of patient A. W., age 46, B.P. 128/90, diagnosis, rheumatic heart disease; under treatment with digitalis The record is abnormal in form; note the doubled J wave and the slight notch in H-I *F*, ultralow-frequency record of patient W. E, age 50, B P. 220/126. Note abnormally small and deeply divided J waves, and the flat or notched H waves. The high opposing hypertension has retarded ejection from the left side *G*, high-frequency record of J. C, age 73, B P 130/92, diagnosis, angina pectoris, under treatment with digitoxin. Note extremely small amplitude and abnormal form The largest wave is the H wave *H*, ultralow-frequency record of H R, age 34, B.P 104/80; diagnosis, rheumatic heart disease with mitral stenosis Note small amplitude and notch on I wave *I*, high-frequency record of S. C., age 28, B P. 160/0, diagnosis, rheumatic heart disease with aortic regurgitation. Note huge amplitude and deep notch on I-J segment

originally chosen did not altogether accomplish this purpose, and many published records lie between velocity and displacement These records look like those secured from a high-frequency table when the subject lies on it without his heels against the footplate and without other means of attachment to the table. These shin-bar records usually show more after-vibrations in diastole and there is more undesirable resonance than in the table records. Direct body records are not easy to calibrate and most doctors do not attempt calibration; however, some apparatus sold has been calibrated at the factory. In the absence of calibration, the height of the record has no meaning but many abnormalities of form are clearly shown. Some investigators have interested themselves in the first and second derivatives of these records in the hope that myocardial abnormalities would be more easily identified in them. Such records are shown diagrammatically in Fig. 4-76, Right. A most interesting development has been the attempt to neutralize the distortions of the direct body record by electrical means, using mixing circuits similar to those of the analog computer.

MEANING OF THE RECORD

The expulsion of blood by the heart applies to the body a set of opposing forces of approximately equal intensities but differing in their time relations The human body is itself composed of variably connected structures of different vibrational characteristics The resulting motion of the body is inevitably complex and difficult to analyze. The movements of the body are related to the magnitude of the forces employed in propelling the blood; this was

severe anemia, and aortic regurgitation. *Increased amplitude is also found* in many patients in which a diagnosis of neurocirculatory asthenia has been made, but not in all, and in some cases with advanced pulmonary disease.

Records *abnormally small* are encountered in a wide variety of clinical conditions They are found in any moribund person, in myxedema, and in many cases of severe heart disease.

Records *abnormal in form* are seen in many varieties of cardiac states, and in many patients suffering from diseases such as diabetes and hypertension, in which cardiac involvement is a common complication *Abnormal records are often found in many* persons past middle age having history or physical findings suggesting heart disease and in whom *the electrocardiogram* is negative This most interesting group will be discussed later

Changes in the Records of Individual Patients. Alterations of form and amplitude with changing conditions of disease are often conspicuous. The *anginal attack* causes a marked deterioration in the record, which improves rapidly after administration of nitroglycerin (Starr). Records taken during the *acute stage of myocardial infarction* are usually highly abnormal, but *this is not necessarily so* These records usually improve slowly during convalescence, and complete normality may or may not be attained. *Arryhthmias*, like atrial fibrillation, may be accompanied by abnormal records which may or may not return to normal when sinus rhythm returns Extrasystoles may be accompanied by abnormal records while the *normal* beats give *normal* ballistocardiograms *Congestive failure* is usually, but not always, *accompanied by abnormal records*, the *exceptions* probably belonging to the group which is now called high *output failure*. Improvement of the congestion is often *accompanied by improvement* in the record, but not always

In *older people* any *major surgical procedure is likely to* be followed by deterioration of the ballistocardiogram, *which slowly* clears up as strength is regained

Effects of Therapy. These are often extremely striking. *Digitalis has* a profound effect on *the records* of patients with heart disease, often causing the greatest improvement in records that were formerly highly abnormal, but this does not always follow, and digitalis given to a person with a normal heart may cause marked *deterioration* of the record. *Therapy for hyperthyroidism* may cause a grossly abnormal record to *return to normal*. The improvement when *myxedema* is treated is very striking. *Nitroglycerin* will often cause temporary improvement *in the record* of elderly persons even though they do not suffer from angina, but occasionally deterioration of the record follows the taking of this drug. The lowering *of the blood pressure in hypertension* may *be accompanied* by marked improvement in the ballistocardiogram; again, it *may not.*

The modern *cardiac operations* are likely to be finally followed by great improvement in the record, but it often deteriorates markedly in the immediate postoperative period, as the *immediate* adverse effects of the cardiac operations are sometimes greater than is usually realized.

SPECIAL TESTS

The simplest test is to have the subject, while the record is running, *take a deep breath*, a maneuver which draws not only air but also blood into the chest and so causes better filling, first of the right heart and later of the left. This test should be made routinely. If the record *improves in form or increases in* amplitude, or both, the heart is on the normal side of the Starling *curve* and *it can* do better than its previous performance indicated. Often such improvement is very striking. If taking a deep breath does not improve the record, the interpretation is somewhat more guarded for pulmonary disease may interfere with the test or the patient may not have followed instructions. In a few healthy persons, taking a deep breath does not always cause an increase in ballistic *amplitude, although it does in* the great majority Despite these reservations, which *increasing* experience may well allow us better *to define*, this simple test gives valuable information.

A record of the position of the respiratory cycle on the ballistocardiogram often helps to interpret the record because there is every reason to believe that, when inspiration begins, increased filling of the right heart *precedes that of the left If*, for example, the J wave is double, *and if one* of the peaks *regularly increases in* amplitude *in* the beat immediately following the beginning of *inspiration*, *it is* reasonable to

feet, associated with the beginning of ejection, the blood being accelerated craniad and its recoil driving the body toward the feet. The J wave is due to the sudden impact of the blood against the bifurcation of the pulmonary artery and the arch of the aorta, and to its downward acceleration as the arch is rounded, all uniting to produce a craniad impact that is the largest wave in the normal record. The last systolic wave, the K wave, is toward the feet and with an amplitude that varies with the age of the subject and the type of instrument used. Improvement in instrumentation has greatly reduced its size until, in records taken on young subjects by the new methods, the K wave often does not cross the base line.

In records of the older type, especially direct body records, diastole was often filled with artifacts due to aftervibrations from the force of the preceding systolic deflections, which sometimes reinforced and sometimes opposed the true forces to give a record of small waves which varied from subject to subject. Records of the newer type, *especially records of acceleration from low-frequency tables, show the true diastolic complexes much more clearly.* Noordergraaf's study indicates that *these diastolic deflections are caused, not only by forces associated with movement of venous blood into the heart, but also by forces associated with the tail end of the pulse wave which reaches peripheral arteries after cardiac systole is over.*

Effects of Breathing on the Ballistocardiogram. All ballistocardiograms show a distinct increase in amplitude during inspiration, and the explanation seems obvious Inspiration causes a marked fall in intrathoracic pressure and this causes an increase in the pressure in the two venae cavae, relative to that in the heart. Consequently, during inspiration the heart will be better filled and so, in accord with Starling's law, it contracts more strongly

Effects of Aging. The ballistocardiogram becomes smaller in amplitude as subjects grow older, even though health, commensurate with age, is retained. Its form changes somewhat, for averages taken at different ages show that, as age advances the I and J waves diminish in amplitude while the K waves become more conspicuous.

Abnormalities of Form. In general, ballistocardiograms may be abnormal in one or two of three ways: because they are too *small*, too *large*, or *abnormal* in contour. The first two can be detected only in calibrated records.

The abnormalities of contour are so varied that description in a few words is impossible In abnormal records, the form usually changes from beat to beat with the phases of the respiratory cycle. In some records, only the smallest complex of the respiratory cycle is abnormal in contour, in others all are involved The percentage thus affected is a measure of the severity of the abnormality. Another simple measure of severity, first suggested by Brown, has proved useful. When but one complex of each respiratory cycle is abnormal, this is *Grade 2;* when all are abnormal, *Grade 3,* when the record is so distorted that systole cannot be identified, *Grade 4.* Brown's original *Grade 1,* when the smallest complexes of the respiratory cycle are less than one-half the amplitude of the next larger, must be used with great caution because any healthy person may make his record abnormal, as judged by this criterion, by voluntarily overbreathing

EVIDENCE LEADING TO AN INTERPRETATION OF ABNORMALITIES OF FORM

The Experimental Attack. Many abnormal forms of the ballistocardiogram have been produced experimentally in experiments conducted in cadavers (Starr et al, 1954). When systole is simulated by an injection into the aorta and pulmonary artery which rapidly accelerates, the ballistocardiogram produced is normal in all respects, save that it lacks an H wave. If the injection is accelerated more and more slowly, a point is reached where the I wave disappears although a small J wave remains If the end of the injection decelerates rapidly, a deep K wave appears. If the aorta and pulmonary artery are injected asynchronously, the J wave becomes notched. Records of all these types are frequently seen in the clinic, examples will be found in Fig. 4-77.

Occurrence in Various Diseases. Records *abnormally large* are found in those situations in which cardiac output is increased, such as during excitement, after exercise, and (to a smaller extent) after eating; after administration of certain drugs, such as epinephrine and amyl nitrite; and in such conditions as hyperthyroidism, arteriovenous communication, anoxemia,

severe anemia, and aortic regurgitation. *Increased amplitude* is also found in many patients in which a diagnosis of neurocirculatory asthenia has been made, but not in all, and in some cases with advanced pulmonary disease.

Records *abnormally small* are encountered in a wide variety of clinical conditions. They are found in any moribund person, in myxedema, and in many cases of severe heart disease.

Records *abnormal in form* are seen in many varieties of cardiac states, and in many patients suffering from diseases such as diabetes and hypertension, in which cardiac involvement is a common complication. *Abnormal records* are often found in many persons past middle age having history or physical findings suggesting heart disease and in whom the electrocardiogram is negative. This most interesting group will be discussed later.

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SPECIAL TESTS

The simplest test is to have the subject, while the record is running, *take a deep breath*, a maneuver which draws not only air but also blood into the chest and so causes better filling, [illegible] or both, the heart is on the normal side of the Starling curve and it *can* do better than its previous performance indicated. Often such improvement is very striking. If taking a deep breath does not improve the record, the interpretation is somewhat more guarded for pulmonary disease may interfere with the test or the patient may not have followed instructions. In a few healthy persons, taking a deep breath does not always cause an increase in ballistic amplitude, although it does in the great majority. Despite these reservations, which increasing experience may well allow us better to define, this simple test gives valuable information.

A record of the position of the respiratory cycle on the ballistocardiogram often helps to interpret the record because there is every reason to believe that, when inspiration begins, increased filling of the right heart precedes that of the left. If, for example, the J wave is double, and if one of the peaks regularly increases in amplitude in the beat immediately following the beginning of inspiration, it is reasonable to

suppose that this peak is caused predominantly by forces emanating from the right heart.

Myocardial abnormalities not detected by ballistocardiograms taken at rest may at times be demonstrated by subjecting the heart to stress, and because of the ease of taking repeated records the ballistocardiograph is well suited to such tests.

An *exercise test* is often used to bring out ballistic abnormalities but a word of caution is needed Records cannot be secured during exercise but they may be taken immediately after the exercise is over, and long before its effects have passed off. Unfortunately, records taken immediately after exercise are made before the subject has had time to relax and so they are far more subject to artifacts than are the usual records taken after the patient has had a 15-min rest on the table, thus there is much to trip the unwary doctor Occasionally a record, previously abnormal, improves after exercise, a fact unexpected and at first thought most puzzling But one is not surprised when an abnormal heart improves its function after a stimulant drug, and one need not be surprised if some hearts likewise improve after the physiological stimulation of exercise

Cardiac abnormalities may be brought out by inducing *hypoxemia*, and as the patient's position remains unchanged during such a test, artifacts are less likely to appear than in records made after exercise.

Marked deterioration of the ballistocardiogram *after smoking* is one of the surprises of the field as it was altogether undetected by the older clinical methods This adverse reaction to smoking is almost never seen in healthy young adults, and the proportion of healthy persons showing it increases as age advances Such a large proportion of persons with manifest coronary heart disease show this abnormal reaction that it has been suggested as a test to aid in the diagnosis of this condition

UTILITY OF THE BALLISTOCARDIOGRAM

The ballistocardiograph is a physiological instrument designed to provide information about certain fundamental aspects of the heart's function, its strength or weakness, and the coordination or incoordination of the forces developed by its contraction Important changes in these cardiac functions may or may not accompany the anatomic and descriptive abnormalities which form the basis of most cardiac diagnoses made today. One should look at the information secured from ballistocardiograms much as one regards that from estimations of blood pressure. The primary purpose is not to enable one to make a familiar anatomic diagnosis with more confidence, but to obtain additional information about the physiological condition of the patient's heart.

It is common experience that, during or after the effects of illness or operation, when one must lift a weight, the skeletal muscles perform the task not only weakly but also with tremor, as if the individual fibers had lost the fine coordination which makes the normal contraction so smooth and easy. Apparently the weakened heart behaves similarly and the abnormal notches and peaks which are found in so many abnormal ballistocardiograms represent a failure of the different parts of the heart muscle to contract with their usual coordination.

The interpretation of ballistocardiographic findings will naturally vary under different circumstances and the heart's external difficulties must always be taken into account. Thus, if the ballistocardiogram is reduced in amplitude in the presence of a marked hypertension, the finding would naturally be interpreted differently than if the opposing pressure were normal. Thus, in hypertension, a low record would be of less significance, and one might hope that if the pressure were reduced it would return to normal.

Similarly, if hypertension opposed the ejection of only one side of the heart, this would be a contributing reason for a split J wave in the record, as the increased resistance retarded the forces of ejection from that side; so the finding would be differently regarded than if no contributing factor were discovered and the split J wave had to be attributed solely to myocardial weakness on one side.

But in many cases of hypertension the ballistocardiogram remains altogether normal as the heart muscle meets its difficulties by increased strength of contraction. This must be remembered before one is tempted to dismiss, as unimportant, abnormalities found in the presence of hypertension When hypertension is reduced, the record returns to normal in some patients while in others it does not.

If the patient is under therapy with digitalis,

this must be taken into account when interpreting the records. Although this drug often converts many abnormal records to normal, if it fails to have this effect, one may properly believe that a more advanced stage of cardiac abnormality has been reached. Thus, the record of the effect of the drug aids one in assessing the degree of myocardial disability. Indeed, the authors are confident that, in the future, differences in the responses to many drugs will be increasingly recognized as a means of discovering functional abnormalities of many sorts. To the careful physician, drugs are diagnostic tools as well as therapeutic agents A good doctor is alert to the true effects of the therapy he undertakes His duty is not limited to prescribing the agent most likely to be successful, and he must make sure that his agent is producing the desired effect on the patient. The ballistocardiogram is well suited to aid him when therapy is directed at the heart

In addition to finding situations and agents which benefit his patient, the doctor must also be alert to discover those that do harm, and the ballistocardiogram is also well suited to this purpose The cardiac disorganization produced by tobacco in certain persons is striking, and it is hard to believe that those who suffer from such adverse reactions would not benefit by abstaining from tobacco

In the well-recognized types of heart disease, the ballistocardiogram indicates the extent to which the muscle has been affected Thus, *many* young persons with advanced rheumatic heart *disease give records that* are normal or nearly so, though others unhappily do not.

In some cases of acute myocardial infarction the record *taken at rest* remains normal during the acute episode, doubtless when the lesion is a small one In many other cases of cardiac infarction *myocardial* function is seriously compromised. Such *differences* seem well worth knowing, as does the degree of myocardial recovery which *is later attained*

Most cases of angina *pectoris* have small, distorted records, but in some the *resting* record is altogether normal between attacks If this is the case, the lesion may be *presumed to* be a small one, everyone knows *how much* pain a small cutaneous lesion may cause

In congestive heart failure the usual ballistocardiogram is small and distorted, but in some cases it is not only normal but unduly large Such a finding permits ready detection of the type called "high output failure," which is seen most often in pulmonary disease, in the authors' experience. Such distinctions are certainly well worth making, as the mechanism gone wrong must be altogether different in the two cases, and one would suppose that proper therapy would be different also.

Besides giving information about the quality of the heart beat, knowledge of the ballistocardiogram often permits one to make distinctions between other conditions concerned with the circulation. Thus, most cases of essential hypertension have ballistocardiograms normal or small in amplitude, but some do not. When hypertension with a large ballistocardiogram is encountered, an epinephrine-like type of response, the physiological mechanism of such a condition must be different from the usual type, and one would expect that the therapy would be different also. By its large ballistocardiogram, the hypertension of excitement is usually readily distinguished from the more serious types, but the authors have also seen large records accompany hypertension eventually traced to a pheochromocytoma

Similarly the functional abnormalities of the circulation such as neurocirculatory asthenia may often be recognized by a resting record abnormally large in size, or by tests designed to demonstrate incoordination of the circulation Unduly large records are also often found in hyperthyroidism, aortic regurgitation, anemia, hypoxemia, arteriovenous communications, fever, and anxiety. But myocardial deterioration, a common complication in many of these conditions, often prevents the usual augmentation For example, one gets the impression that, in hyperthyroidism, myocardial complications are more frequent than is generally realized.

There is an important question on which the last word has not been said How should one regard the large number of subjects over 50 years of age who have no symptoms suggestive of heart disease, in whom the routine cardiac studies are negative, but who have distinctly abnormal ballistocardiograms (Scarborough et al., 1953)? The facts with regard to this situation are as follows First, it is extremely infrequent in young persons, and occurs with increasing frequency as age advances; so the proportion of individuals showing abnormal records at different *ages is quite* similar to the

percentage of individuals showing coronary arteriosclerosis at necropsy at these ages. Second, a number of these subjects, followed for a period of years, have eventually developed angina pectoris or cardiac infarction, and most doctors using ballistocardiograms have had experience of this kind. Third, many of these persons, but not all, given nitroglycerin while lying on the ballistocardiograph, respond by improvement in their records, sometimes to the extent of a return to normal, a point of similarity with many cases of clinical coronary heart disease Fourth, a few of these cases (the authors have three of these), followed to necropsy have indeed had severe coronary arteriosclerosis.

Such evidence raises the question as to whether physicians do not now possess the means of identifying coronary heart disease before the clinical picture develops, and if so they should at once consider means of prevention in any patient with an abnormal ballistocardiogram not otherwise accounted for On the other hand, there is no doubt that cardiac infarction can occur in patients who recently had a normal ballistocardiogram, and also that many elderly patients with abnormal records have gone many years without developing the clinical picture of coronary heart disease.

When one encounters an abnormal ballistocardiogram in an otherwise healthy elderly person, the course of action should be as follows The evidence does not justify frightening the patient by a prediction of disaster made either to him or to his family However, elimination of tobacco use and reduction in the fat content of the diet should be advised While the success or failure of such a program is difficult to assess, the patient has nothing to lose by trying it.

The authors themselves have reservations about the ballistocardiographic diagnosis of coronary heart disease. Owing to the emphasis on anatomical lesions, which is the heritage of the great pathological school, too many doctors seem inclined to forget that the heart often weakens and finally ceases to beat as a result of disease elsewhere in the body, of electrolyte imbalance, or of noxious agents acting on it, without the appearance at autopsy of any anatomical change to which its failure could be attributed. The ballistocardiogram will undoubtedly detect such weakening, and it may well occur far more often than is generally realized. There is no reason why an abnormal record in an elderly person should always mean coronary arteriosclerosis

Finally, the detection of organic cardiac lesions is placed last in the category of practical utility. The ballistocardiogram may provide a hint of some of these, but the diagnosis is likely to rest chiefly on other means.

Certainly those whose point of view of heart disease is limited to the anatomical lesions are likely to see little virtue in the instrument. But at autopsy, the heart is no longer beating, and for this reason the autopsy picture of cardiac disease is extremely imperfect. While beating, the heart produces forces which move the body, and from a study of these forces, knowledge, both of heart disease itself and of the effects of therapy upon it, is increased. Surely this is new knowledge of fundamental cardiac functions, and one should not lack means of using it for the benefit of those who entrust themselves to one's care.

ORIGIN OF THE BALLISTIC MOVEMENTS OF THE BODY

Where does the ballistocardiogram originate? This is still a question of prime importance Some answers already have been suggested These answers tell of abnormal patterns related to *myocardial damage*, of changes in pattern size dependent upon changes in the magnitude of *the volume of blood* ejected at each beat of the heart, of some variation in pattern with *aortic insufficiency* and with *constrictive pericarditis*, and, with certain types of ballistocardiographs, an abnormal pattern associated with *coarctation of the aorta* or other interference with the flow of blood in the descending aorta.

The accumulating evidence appears to indicate that the ballistocardiogram originates in the movement of blood from the heart during the period of ejection and the subsequent motions of the blood in the vascular system. These findings on the origin of the ballistic patterns have been reported more or less consistently by workers using the three major types of ballistocardiographs—namely, the high-frequency system of Starr, the low-frequency, critically

TABLE 4-7. VARIATION OF BALLISTOCARDIOGRAMS WITH TYPE OF INSTRUMENT

Type of BCG*	Frequency n, cycles per second														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	100	189	169	42	33	21	23	12	5	18	6	1	3	1	3
2	100	241	359	*137*	*97*	*89*	65	*31*	*40*	*10*	*9*	*31*	*14*	*16*	*1*
3	100	329	607	653	1,158	986	444	182	265	61	69	31	120	18	38
4	100	44	19	95	127	66	4	42	36	9	14	1	1	4	4

* 1 Low-frequency, critically damped type of Nickerson 2 Middle-frequency 3 High-frequency type of Starr 4 Direct type of Dock.

damped system of Nickerson, and the direct instrument of Dock However, it must be *pointed out that the quantitative estimates* are best made by the low-frequency, critically damped, or the high-frequency systems, while *the coarctation* pattern is most impressive and consistent when demonstrated on low-frequency, critically damped systems

Because of the variation in the consistency of the results when different *ballistocardiographs* are used, it is necessary to restate the original question in a simpler and more basic form. What is the *basic force pattern* producing the ballistocardiogram? This question leads to a further question, namely: How accurately can a *ballistocardiograph* record the true force function?

One method of seeking this basic force function is to *submit the* ballistocardiogram to a form of frequency analysis known as *Fourier's analysis* This analysis will provide an equation to represent the ballistocardiographic pattern in the general form.

$$Y = A_0 + A_1 \sin (w_0 t + \theta_1) + A_2 \sin (2w_0 t + \theta_2) + \quad + A_n \sin (n w_0 t + \theta_n)$$

where A_0, A, etc = amplitude coefficients
θ_0, θ_1, etc. = phase angles
$w_0 = 2\pi n_0$
n_0 = fundamental frequency of repetition of the pattern, cps

In 1952 Braunstein reported the analysis of a *few* ballistocardiograms recorded from a high frequency instrument *In* 1954 Nickerson and Mathers reported Fourier analyses on ballistocardiograms of seven subjects, studied with four different *ballistocardiographs*. This study demonstrated that, not only did the amplitude coefficients differ from subject to subject, but also as expected from the appearance of the records, marked differences were found between records taken on the same subject with different ballistocardiographs (Table 4-7).

Casual *examination* of Table 4-7 suggests that the formula will represent the ballistic curve quite well if carried out to only 11 or 12 cps. However, it has been suggested that it may be necessary to consider *components* out to 20 or 30 cps This may be true for fine detailed analysis of the *shape* of the curves but is probably *unnecessary for the* estimation of *stroke volume* since most of the energy lies in the ultralow-frequency end of the spectrum

Although the four patterns and the corresponding analyses given in Table 4-7 *originate* in the same heart, they are all considerably different. Herein lies the necessity of determining how well the *ballistocardiograph* represents the original force function and to what extent this force pattern is altered by its passage through *the body and* in the act of imparting movement to the ballistic bed.

There are two general directions of investigation *in the attempt* to answer this question. One approach, made by Nickerson and Mathers, was to correct the pattern for errors introduced *by its* transmission through the body and by the response of the *bed. It* has been pointed out by Burger that the assumptions in *this first* attempt were oversimplified since coupling interaction between *the* body and bed oscillators was ignored. However, the more *precise* analysis considering the body and bed as coupled *oscillators does* not markedly change the conclusions to be drawn over the range of

frequencies originally studied, i.e., up to 12 or 15 cps.

The conclusions drawn from this simple study were that, although none of the ballistocardiographs then in current use, namely, the Nickerson, the Starr, and the Dock types, gave perfect agreement with the corrected pattern, nevertheless the Nickerson instrument approximated the *velocity pattern* and the Starr instrument the *acceleration pattern*.

The other general approach to the problem was to use an ultralow-frequency system. This was essentially the instrument of Gordon and Henderson and was advocated by Nickerson and Curtis but not used by them for reasons of expediency. Burger, von Wittern, Talbot, and others have recently used the ultralow-frequency system. It is assumed that this method minimizes the distortion introduced into the pattern as the impulses travel from its origin in the region of the heart through the body and to the ballistocardiograph.

Whether or not this assumption is correct is not obvious Recent work by Nickerson consisting of theoretical studies on the ballistocardiograph as a system of three stages of coupled oscillators having various degrees of damping have indicated that no system is perfect and that the preference for the ultralow-frequency system is perhaps not necessarily as final a choice as would appear according to the current literature

In all considerations directed at finding the true internal forcing function it must be remembered that the body is not a single compact mass but has distributed masses in head and limbs. It is, therefore, most difficult to decide on its basic oscillation constants. Although at lower frequencies the body oscillates in a predictable fashion as a unit, at higher harmonics, such as those frequencies approximating the natural periods of the appendages, these parts may be set into exaggerated motion so that the problem of tracing back to the interior of the body in order to determine the original forcing function becomes most difficult.

In concluding these speculations on the origin of the ballistocardiogram, it appears that the force functions arise in the activity of the heart in ejecting blood and in the flow of blood in the large vessels of the aortic and pulmonary systems. Whether the true activities of ejection and flow remain separable in the pattern is not always determinable. In the case of a greatly stiffened aorta, it is probable that the simple recoil due to ejection may have associated with it at the same time the impacts due to the movement of blood in the further reaches of the aortic tree. Whether any of the presently advocated types of ballistocardiographs give a perfect representation of the basic forcing function is a question still requiring experimental demonstration.

5

Basic concepts in the use of radioactive isotopes

ABRAHAM R. GOLDFARB

INTRODUCTION

Radioactive isotopes are used *diagnostically* in cardiology and in cardiovascular diseases principally for the determination of plasma volume and red-cell volume, for the determination of cardiac output, and for the examination of the rate and type of flow of blood through the heart (radiocardiography) *Therapeutic use* of isotopes is restricted at this time to the use of I^{131} as NaI to reduce thyroid activity in cardiac cases where this is desirable and where surgery and antithyroid drugs are contraindicated These uses are described in some detail elsewhere in these volumes and will not be discussed here. This chapter will attempt to define and explain the terminology in respect to the applications of radioactive isotopes.

The use of radioactive isotopes is based on two fundamental properties of such isotopes First, *these isotopes react chemically and biologically in the same way as the stable isotope which is normally present* For example, the stable and most abundant isotope of iodine, which has an atomic weight of 127 in the form of the element I_2, is reduced by sodium thiosulfate and, as the ion I^-, is preferentially concentrated by the thyroid gland and converted into thyroid hormone The *radioactive isotope of iodine with an atomic mass of 131* is made in a nuclear reactor and emits a *beta* particle and *gamma* radiation Except for the emission of the radiation, this isotope of iodine shows the same chemical, physical, and biological reactions as the isotope described above The second fundamental property of radioactive isotopes is *the emission of radiation* which can be detected with the proper instruments. An example of this would be the determination of the amount of I^{131} concentrated in the thyroid gland by placing a Geiger-Muller counter or a scintillation detector externally near the thyroid and determining the activity.

ATOMIC AND NUCLEAR STRUCTURE

An element consists of a *nucleus* and a cloud of *electrons* surrounding this nucleus According to the Bohr representation, the nucleus and the surrounding electrons are pictorially shown as a planetary system with the nucleus in the center and the surrounding electrons in orbits rotating around the nucleus. In Fig 4-78 is shown a schematic representation for two elements, namely, *hydrogen* with a nucleus and a single planetary electron, and *sodium* with a nucleus and eleven electrons around it. The principal chemical and

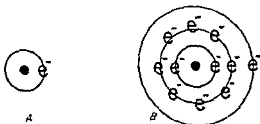


Fig. 4-78. Bohr models. A. Hydrogen atom. B. Sodium atom The nucleus is represented by the solid circle; e^- is the electron which revolves around it.

frequencies originally studied, i.e., up to 12 or 15 cps.

The conclusions drawn from this simple study were that, although none of the ballistocardiographs then in current use, namely, the Nickerson, the Starr, and the Dock types, gave perfect agreement with the corrected pattern, nevertheless the Nickerson instrument approximated the *velocity pattern* and the Starr instrument the *acceleration pattern.*

The other general approach to the problem was to use an ultralow-frequency system. This was essentially the instrument of Gordon and Henderson and was advocated by Nickerson and Curtis but not used by them for reasons of expediency Burger, von Wittern, Talbot, and others have recently used the ultralow-frequency system. It is assumed that this method minimizes the distortion introduced into the pattern as the impulses travel from its origin in the region of the heart through the body and to the ballistocardiograph.

Whether or not this assumption is correct is not obvious Recent work by Nickerson consisting of theoretical studies on the ballistocardiograph as a system of three stages of coupled oscillators having various degrees of damping have indicated that no system is perfect and that the preference for the ultralow-frequency system is perhaps not necessarily as final a choice as would appear according to the current literature.

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... and their radiations are shown in ... seen from the table that more than one beta particle, or more than one unit of gamma radiation, can be emitted during nuclear decay. This is of considerable importance in using various radioisotopes and the energy of each type of radiation determines the application of an isotope.

It can be stated as a general rule that radiation penetrates matter to a varying degree and the amount of penetration will increase with the increase in energy of that radiation. It therefore would appear that matter absorbs radiation and the mechanism of this absorption should be explained. If one considers the structure of matter, one could show that it consists of very minute nuclei having a nuclear diameter of the order of 10^{-13} cm whereas the whole atom has a radius of the order of 10^{-8} cm. Therefore the largest part of the volume of an element is the cloud of surrounding electrons. When charged particles, such as the *alpha* particle (with two positive charges) or the electron (with a single negative charge), pass through matter, they will either attract or repel the electrons closest to them. In so doing, they will cause the most loosely bound electrons of an atom to be removed from the immediate vicinity, and what is known as an *ion pair* will be formed from the original neutral element. The ion pair consists of one electron separated from a particle having a single positive charge. A second electron is rarely removed from an element in this "ionization." Since it requires energy for one electron to be removed from its element

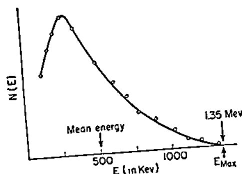


Fig. 4-79. Beta particle spectrum of K^{40}.

(cathode 32 ev), the energy of the particle is decreased. Therefore, as a particle penetrates matter, it gives up its energy, causing a whole series of ion pairs to be formed and since, as it was pointed out above, the energy of the particle is related to its velocity, the particle slows down and ultimately stops. The total distance which the particle penetrates through matter is called the *range*. The electromagnetic radiation is absorbed by matter through absorption of energy by the whole atom and the expulsion of an electron. This type of conversion is easily illustrated by the various types of photoelectric instruments which are in use today.

As a first approximation, the range of an *alpha* or a *beta* particle is inversely proportional to the density of the medium through which it travels. For example, an *alpha* particle having an energy of 5 Mev has a range in air of 3.5 cm and, since air has a density 0.00129 that of tissue, the range of this particle in tissue is 0.00129×3.5 or 0.0045 cm. It is customary to express this range in *microns* (μ) and, therefore, the range in tissue of a 5-Mev particle is 45 μ. The *alpha* particles are principally obtained from the heavy elements such ...

TABLE 4-9 SOME COMMON RADIOACTIVE ELEMENTS AND THEIR RADIATIONS, IN MEV

Element	*Alpha particle*	*Beta particle*	*Gamma radiation*
Tritium	None	0.011, 0.015	None
Sodium^{24}	None	1.4	1.4, 2.8
Iron^{59}	None	0.26, 0.46	1.1, 1.3
Phosphorus^{32}	None	1.71	None
Iodine^{131}	None	0.6	0.37, 0.08
Thorium^{232}	4.2	None	None
Mesothorium^{2}	4.5	1.55	None
Radium^{226}	4.79	None	0.19

in medicine at this time. ... by a radioactive isotope consists of a whole spectrum of individual particles, all having different energies. If the number of particles having a given energy (N_E) is plotted against the energy content, the result is a curve such as that shown in Fig. 4-79. There are two terms of significance in this figure, the mean energy and the maximum energy (E_{max}). The mean energy is used to calculate the number of roentgens, whereas E_{max} is used to identify an element and also determines the total range of a *beta* particle from such an element. *Beta* particles have a range in human tissue of the order of magnitude of centimeters. For example P^{32} *beta* particles will penetrate as much as 1.1 cm of tissue. *Gamma* radiation is the most penetrating

TABLE 4-8. NUCLEON COMPOSITION OF SOME COMMON ELEMENTS AND THEIR ISOTOPES

Element	*Protons*	*Neutrons*	*Atomic no*	*Atomic mass*	*Symbol*
Hydrogen	1	0	1	1	$_1H^1$
Deuterium	1	1	1	2	$_1H^2$
Tritium*	1	2	1	3	$_1H^3$
Sodium	11	12	11	23	$_{11}Na^{23}$
Sodium*	11	13	11	24	$_{11}Na^{24}$
Iron	26	30	26	56	$_{26}Fe^{56}$
Iron*	26	33	26	59	$_{26}Fe^{59}$
Phosphorus	15	16	15	31	$_{15}P^{31}$
Phosphorus*	15	17	15	32	$_{15}P^{32}$
Iodine	53	74	53	127	$_{53}I^{127}$
Iodine*..	53	78	53	131	$_{53}I^{131}$

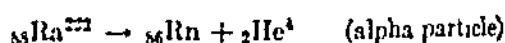
* Radioactive

physical properties of the element are determined by the electrons surrounding their respective nuclei. The *electron* is a particle which is 1/1024 of the mass of a hydrogen nucleus and has a single negative charge associated with it. According to the facts which require that an element be a neutral particle, the nucleus has a positive charge equivalent to the number of electrons around the nucleus. It has been further shown that the nucleus contains practically the total mass of the atom. The structure of the nucleus is the critical factor in determining whether an element is stable or whether it is unstable and radioactive.

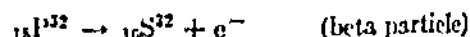
The nucleus essentially consists of two types of particles (*nucleons*), i e., the *proton* and the *neutron*. The proton is a particle of mass 1 and has a single positive charge associated with it. The *neutron is a particle of mass 1 but has no charge.* The symbol for the proton is p and the symbol for the neutron is n. The *atomic number* has been defined as the number of electrons around the nucleus. Since, as stated above, the element is neutral and the nucleus has a positive charge equivalent to the number of electrons, the nucleus must contain a number of protons equivalent to the total positive charge on the nucleus. Therefore, the new definition of atomic number is the number of protons present in the nucleus In order to explain the occurrence of *isotopes* (elements which have the same atomic number but different atomic weights) it is reasonable to presume that the difference is due to the presence of different numbers of neutrons From this, the *atomic mass,* which is a measure of *atomic weight,* is estimated as *the sum of the number of protons plus the number of neutrons in the nucleus*

In Table 4-8 is listed a set of isotopes of some of the more important elements in which the starred (*) individuals are radioactive. It is customary to write an element in the form $_aX^b$ where a is the number of protons and b is the number of protons plus the number of neutrons. These symbols are *included in the table.*

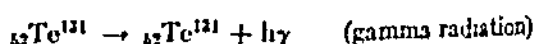
It is evident that some elements have isotopes which emit radiation and others which do not. Careful studies in nuclear physics showed early that most elements that emit radiation may be converted to new elements, e.g., I^{131} emits *beta* and *gamma* radiation and is converted to *krypton*[131] It is a general rule that, if an *alpha* particle is lost, the atomic number of the new element formed is numerically two less than that of the original radioactive element and the atomic mass is four less. If a *beta* particle is emitted, the new element formed has an atomic number numerically one greater than that of the original radioactive element, with no change in atomic mass. If *gamma* radiation is emitted, the element remains the same with respect to both atomic number and mass. Several examples of this follow:



$_{88}Ra^{222} \rightarrow {}_{86}Rn + {}_2He^4$ (alpha particle)



$_{15}P^{32} \rightarrow {}_{16}S^{32} + e^-$ (beta particle)



$_{52}Te^{131} \rightarrow {}_{52}Te^{131} + h\gamma$ (gamma radiation)

NUCLEAR RADIATIONS

When a radioactive nucleus undergoes a change, any of three types of radiation or some combination *of them is produced.* These radiations are *alpha* and *beta* particles and *gamma* radiation.

The *alpha particle* is the nucleus of $_2He^4$, or a helium atom of atomic weight four with the two planetary *electrons removed. The beta particle* is also known as an electron. It has a single negative charge and a mass 1/1024 that of the proton. These are the same particles which surround the nuclei to *form a neutral element. Gamma radiation* is electromagnetic radiation which is identical in all respects to x-rays, except that the wavelengths are much shorter. Grossly the x-rays obtained from a million-volt x-ray machine *is the same* as gamma radiation having an energy of one million electron volts All radiations emitted by radioactive isotopes are associated with a given amount of energy The energies of the particles are kinetic energies and are related to the velocity of the particle by the expression $E = \frac{1}{2}mv^2$ Electromagnetic radiations have energies which are related to their wavelengths by the expression

$$E = hc/\lambda$$

where E = energy
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The unit in which the energies are expressed is the *electron volt,* i.e., the amount of work performed when one electron is accelerated by a po-

tential difference of 1 volt. The electron volt is abbreviated as ev and is usually given in units of one thousand (kilo, *Kev*) or one million (mega, *Mev*).

It has been indicated above that each decaying nucleus can emit either one or several radiations. Several examples of common radioactive elements and their radiations are shown in Table 4-9. It is seen from the table that more than one beta particle, or more than one unit of gamma radiation, can be emitted during nuclear decay. This is of considerable importance in using various radioisotopes and the energy of each type of radiation determines the application of an isotope.

It can be stated as a general rule that radiation penetrates matter to a varying degree and the amount of penetration will increase with the increase in energy of that radiation. It therefore would appear that matter absorbs radiation and the mechanism of this absorption should be explained. If one considers the structure of matter, one could show that it consists of very minute nuclei having a nuclear diameter of the order of 10^{-13} cm whereas the whole *atom* has a *radius* of the order of 10^{-8} cm. Therefore the largest part of the volume of an element is the cloud of surrounding electrons. When charged particles, such as the *alpha* particle (with two positive charges) or the electron (with a single negative charge), pass through matter, they will either attract or repel the electrons closest to them. In so doing, they will cause the most loosely bound electrons of an atom to be removed from the immediate vicinity, and what is known as an *ion pair* will be formed from the original neutral element. The ion pair consists of one electron separated from a particle having a single positive charge. A second electron is rarely removed from an element in this "ionization" Since it requires *energy* for one electron to be removed from its element

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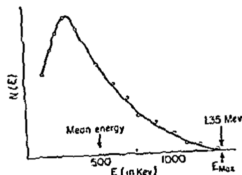


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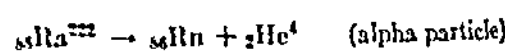
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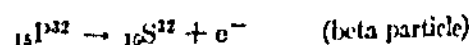
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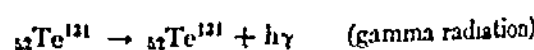
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The unit in which the energies are expressed is the *electron volt*, i.e., the amount of work performed when one electron is accelerated by a po-

called the proportional region. From point C to point D there is only a very slight rise in the number of cpm (about 1 per cent/100 volts) with increasing voltage, and this region is known as "the Geiger or plateau region." This region extends for about 300 volts The part of the curve from C to D is called "the region of continuous discharge" and is a region where a nonspecific, electrodeless discharge occurs. From an examination of this curve it can be seen that the voltage to be used for each tube may vary within limits which are determined either by the manufacturer or by the user The best voltage, for most uses, is that which is 100 volts above point *B* since, if the line voltage drops for any reason, the counter will still be working in the plateau region Also, it is not desirable to work closer to the region of continuous discharge since an increase in line voltage will throw the instrument into the region of continuous discharge, thus giving high results Geiger-Muller counters have various shapes and forms which are adapted for various uses. The impulse which is derived from a tube is passed through a *scaler* which is a device for recording and adding the individual impulses There are two types of scalers used at present, one is the "64 scaler", the other is the "decade scaler" As the names indicate, the first counts the impulses in multiples of 2 up to 64 and at the 64th it activates a mechanical register The latter counts in multiples of 10 and has a mechanical register which acts similarly It is sometimes desirable to make a continuous recording of the intensity of the radiation, in which case one uses a *count rate meter* which measures the rate in cpm rather than the total number of impulses Count rate meters have arrangements for attaching continuous recording devices In analytical work, where one desires to obtain precise values of the activity of a sample, one uses a scaler, rather than a count rate meter since the latter has intrinsic errors which make the best precision unavailable The precision of the results for the count rate meter, however, is satisfactory for continuous recording requirements since the relative error remains the same and it is only necessary to obtain the shape of a curve in relation to the passage of time.

Alpha and *beta* particles and *gamma* radiation can all be analyzed using G.M counters. The techniques for analyzing *alpha* particles in windowless counters are described elsewhere and have no special importance in cardiology. *Beta* particles of all energies are analyzed with a high degree of accuracy by G M. counters Although *gamma* radiation can be analyzed well with special G M. tubes, the counting efficiency is very low, i e., of the order of magnitude of 1 to 7 per cent.

In recent years a considerable amount of work has been done using *scintillation counters.* The scintillation counter operates on the same basis which is used in x-ray fluoroscopic screens except that the screens used in fluoroscopy usually consist of a phosphorescent material which is activated zinc sulfide The ZnS phosphor is one which has a slow decay time, so that, when an x-ray passes through it and light is emitted, the light persists for a relatively long period of time In making individual counts for precise work with radioisotopes, it is necessary to be able to make counts of single impulses If the time between impulses exceeds the decay time of the phosphor, false results will be obtained The great search has been for phosphors which have very short decay times—of the order of magnitude of 10^{-8} sec or less Such phosphors are available now in all shapes, sizes, and specifications They usually consist of organic compounds of the aromatic series, e g, anthracene, and can be used either in solid form or in solution The phosphor is attached in some way directly to sensitive photomultiplier tubes which are in turn connected to a scaler which again reads the number of impulses The scintillation counter is being used to a much greater extent today for scanning and counting the gamma radiation from I^{131}

RATE OF DECAY OF RADIOACTIVE ISOTOPES

If a sample of radioactive I^{131} is placed in appropriate measuring equipment and a measurement is made of the activity in cpm, a definite number will be obtained If the activity of the same sample is measured at daily intervals, it is observed that the value goes down quite regularly and, at the end of about a week, the activity is one-half that observed at the very beginning The rate at which the activity of an isotope decreases is called *the decay rate* If one plots the activity (in cpm)

radiation of all. The law which governs the absorption of gamma rays is as follows:

$$I = I_0 e^{-kd}$$

where I = intensity of radiation at a given point
I_0 = intensity of radiation at the entering surface of the absorbing material
k = a constant
d = distance to the point measured

It can be shown that a plot of the logarithm of I against d is a straight line and therefore the thickness of absorbing material necessary to reduce the intensity to one-half the original intensity is always a constant. The term used for a thickness of absorbing material which will reduce the intensity of radiation to one-half of its original value is the *half value layer* (hvl). This is a term which is in general use in roentgenology. The range of gamma radiation in tissues is in the order of magnitude of 10 cm and more.

METHODS OF DETECTION OF RADIATION

It has been indicated above that, when radiation of any sort passes through matter, the energy of the radiation is absorbed by causing ionization to occur in the absorbing matter. A large variety of instruments has been designed to measure radiation by making use of the ionizing properties. Only two are of major interest, i.e., the Geiger-Muller (G.M.) counter and the scintillation counter.

The *G.M. counter* consists of a tube with a central wire in which a high positive potential is applied to the central wire electrode and the wall is metallized and has a negative charge (Fig. 4-80). This schematic diagram illustrates the principles involved in the use of

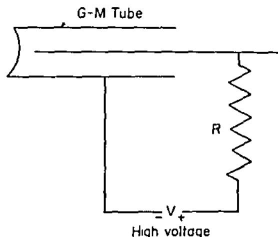


Fig. 4-80. Cross section of a G-M tube connected to a potential, V, through a series resistance, R.

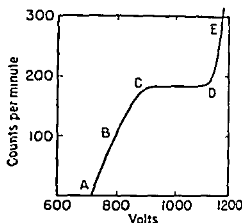


Fig. 4-81. A typical, characteristic curve for a G.M. counter.

the counter. The tube is filled with an inert gas such as argon containing a small amount of an organic gas such as methane. When ionizing radiation passes through the chamber, electrons are formed from the ion pairs. The electrons move to the positively charged central electrode (also called the collecting electrode) and then flow through the external wire, giving rise to a current impulse. At low collecting voltages, the exact value of which depend on the design and specifications of the G.M. tube, there are relatively few electrons captured by the collecting electrode, and there is no current flow that can be readily measured. If now the potential on the central wire is increased, the velocity of the electron in its motion toward the collecting electrode is increased. When the velocity has increased sufficiently, the electron has gained energy so that it can itself become another source for the further formation of free electrons. In this way there is an increase in the number of electrons that reach the collecting electrode (*avalanche phenomenon*). This increase is called the *amplification factor* and, in the usual type of G.M. tube, has a value of about 10^8. If a G.M. tube is connected to a recording device and the number of counts per minute (cpm or c/m) is determined on a sample of constant activity, a curve will be obtained similar to that shown in Fig. 4-81.

At voltages up to point A the acceleration of the electron from the original ion pair is insufficient to initiate a satisfactory avalanche and the resulting current impulse does not activate the scaler. From point A to point B an increasingly larger number of electrons is able to initiate an avalanche. This region is

curie is defined as the amount of material which will give rise to 3.7×10^{10} disintegrations per second (d/s). This should not be confused with the number of counts per second obtained with the usual equipment since, under these experimental conditions, all of the emitted radiations are not recorded by the equipment. However, the d/s is directly proportional to the cpm and the proportionality is easily determined by a method known as *absolute counting* The method of absolute counting is described in detail in a variety of standard textbooks and will not be further discussed here The curie is subdivided into *millicuries* (mcuries, 10^{-3}c) and *microcuries* (μcuries, 10^{-6}c)

CLINICAL USE OF RADIOACTIVE ISOTOPES IN CARDIOLOGY AND CARDIOVASCULAR DISEASE

Isotope Dilution Principle. The clinical use of radioactive isotopes in cardiology and cardiovascular disease is principally dependent on the use of the *isotope dilution principle* If one injects into the blood stream of an individual v ml of a solution of an isotope which has an activity of a cpm/ml, the total number of cpm injected is va When this mixes completely with the total volume of blood V, the specific activity of the blood is va/V. Therefore, it is possible to measure the volume V by determining the activity a of the solution which is injected, injecting a known volume v of the solution of isotope, allowing sufficient time for mixing, withdrawing a sample of blood, and determining the activity, in cpm/ml (calling the last experimental value $cpmV$) A simple expression is obtained.

$$cpmV = va/V \quad \text{and} \quad V = va/cpmV$$

The limiting factor in the use of isotopes for the determination of space volumes is the question whether the volume is sharply defined This question also arises in the use of dyes, e g , T-1824 The two factors which must be defined are (1) Can it be stated that the injected material has been diluted in the particular space under study? (2) How certain is it that there has been no diffusion or leakage into other spaces? The general agreement between results obtained with isotopes and those obtained by other means are, however, in good enough agreement so that the validity of isotope techniques is not questioned at this time.

Cell and Plasma Volumes. The methods used for these determinations depend on the isotope dilution technique. The method of application and the theory of this technique are similar to classical dye techniques. The isotopes used at this time are P^{32}, I^{131} (the radiations of which are given in Table 4-9) and Cr^{51} The earliest methods for determining red-cell volumes involved the use of *red cells tagged with* P^{32}. Chaplin (1954) made a critical study of this method. The red cells of the patient to be studied are incubated, under precisely described conditions, with inorganic phosphate containing P^{32}, during the incubation it is incorporated into the red cell as bound organic phosphorus which is lost from the cell to only a slight extent under the conditions of the cell volume determination. The cells are removed from the incubation mixture and washed thoroughly, mixed with sterile normal saline solution, and a known quantity is injected back into the patient. At suitable intervals, blood samples are withdrawn and analyzed for the activity, in cpm, per unit volume of red cells From this, the red-cell volume is calculated and, with the hematocrit, it can be converted to whole blood volume.

Reilly et al (1954) reported, in detail, the use of Cr^{51}-tagged red cells for the estimation of *the apparent whole blood volume.* The Cr^{51}, in the form of $Na_2Cr^{51}O_4$, was incubated for 45 min at room temperature with a sample of heparinized whole blood from the subject being studied From 60 to 98 per cent of the chromium is taken up by the red cells depending on the amount of carrier (inactive) chromate that is present. It is evident from the studies made that the red cells can be saturated with chromate and, in the presence of an excess, not all of the Cr^{51} will be taken up The cells are centrifuged from the plasma and washed three times with sterile normal saline solution, at this time the supernatant saline solution contains only traces of activity. These *labeled cells* are very stable and lose an insignificant amount of activity on standing overnight The cells are suspended in a given volume of sterile normal saline solution, 0 50 ml of this suspension is removed and diluted to 50.0 ml, 5 0 ml of this diluted suspension is placed in the proper apparatus and the activity

against time one obtains curves like those given in Fig. 4-82A. A plot making use of the same data as the log of the activity against time gives a straight line (Fig. 4-82B). For all isotope studies, the rate of decay follows the law

$$A = A_0 e^{-\lambda t}$$

where A = activity, in cpm, at time t
A_0 = activity at any arbitrarily determined time
λ = decay constant

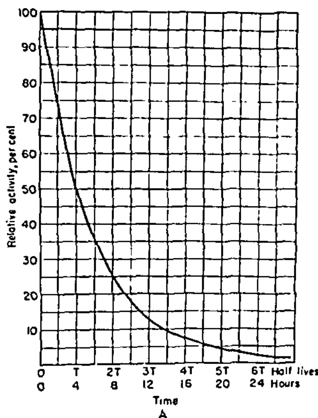
Lists of decay constants for all radioactive isotopes are available in the proper handbooks. For practical purposes, however, it can be shown that another value called the *half life* ($t_{½}$) is in more general use. *The half life is defined as the time which is required for the reduction of the activity to one-half its original value*, and is connected with the decay constant by the expression,

$$t_{½} = 0.693\lambda$$

It is often desirable to calculate what activity is left after an isotope has been stored for some time. This is done by using semilog ruled paper and drawing a straight line from 1.0 to a point which corresponds to the half life on the time scale and to 0.5 on the log A scale.

All isotopes have characteristic half lives which vary from 10^{-6} seconds to 5,000 years. Among the most useful isotopes and half lives are Na^{24} (14.8 hours), P^{32} (14.3 days), and I^{131} (7.9 days). It is quite possible to obtain a "carrier free" isotope, i.e., a radioactive isotope in the completely pure state, containing no other isotope of the same element. In most cases, however, it is more convenient to dilute the radioisotope with a stable isotope of the same element. In the presence of such mixtures, it would not be feasible to mention the use of radioactive isotopes in terms of milligrams unless it was specifically known how much radioactive isotope was contained in 1 Gm of mixture. This is known as the *specific activity*. It should be pointed out that, because of the disappearance of the isotopes with time, the specific activity will decrease with time depending on the half life. The specific activity is usually given as millicuries per gram (mcurie/Gm).

The term used to describe the amount of radioactive material present in a mixture of stable and radioactive isotopes is the *curie*. The



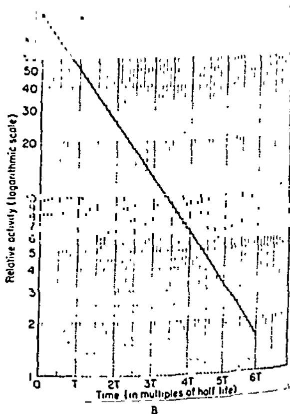


Fig. 4-82. Decay of a radioactive substance. A. Linear plot. B. Plot of logarithm of activity vs. time.

6

Circulation time. Indicator-dilution methods

Circulation Time
WILLIAM M. HITZIG

Radiocardiography
RENZO GALLINI AND ARIO B. ZILLI

Indicator-Dilution Methods
H. J. C. SWAN AND EARL H. WOOD

CIRCULATION TIME

DEFINITION

"Circulation-time methods" attempt to determine the time required for the circulating blood to complete a unit of circulation. *The term "circulation time," however, is a misnomer,* since there are numerous paths through which a blood element or injected substance could traverse a complete circuit, the shortest being through the territory of the coronary arteries Nevertheless, the determination of the circulation time, or the measurement of the speed of blood flow through a selected pathway, has been universally recognized as a valuable procedure at the hospital bedside or on the office examining table, not only for confirmatory diagnosis and the establishment of the degree of circulatory efficiency in cardiac and noncardiac pathological states, but also during therapy, in order to follow the course of myocardial decompensation. Notwithstanding many theoretical objections to circulation-time methods, the narrow range of the circulation time in health and the characteristic alterations in heart failure have justified their use, since their inception, as a rough measurement of myocardial efficiency.

The term "circulation time," as it has been applied in clinical medicine, seems to be poorly defined in the literature where many described methods fail to stress that the circulation time obtained does not actually measure the velocity of blood flow of the entire circulation in man, but only of a limited segment of the total circulation, or only of that measurable portion which includes the pathway through the lungs Unfortunately, the assumption that this point is well known is probably responsible for the failure of most investigators to emphasize that the speed of blood flow differs in various portions of the vascular tree, the differences being largely due to the variations in the caliber of *arteries, capillaries, and veins in the various body* territories Fortunately, some authors have clearly stated that the term "circulation time" implies a measure only of the *mean velocity* of blood flow of an injected substance from the site of injection to the point of detection, or as the approximate inverse of the average velocity of flow between two points As a two-point concept, circulation time represents *the shortest measurable pathway in the vein-to-artery circuit through the lungs*

Since the arterial concentration curve of test substances at designated sites is not known, the minimum circulation *time seems to* be entirely dependent upon the initial concentration

is determined as a standard. A precise amount of the concentrated suspension is injected into the subject. After 30 min of circulation in normal patients (60 min in the case of subjects suffering from cardiac decompensation), the values of blood activity were found constant. From the activity of the 5.0-ml sample drawn, after mixing it together with that of the standard fraction, the red-cell volume can be obtained.

Before the introduction of radioactive isotopes in the study of plasma volumes, this determination was restricted to the use of Evans blue *Krispell, Porter, and Nieset (1950) reported* the preparation of an iodinated human serum albumin (RISA) containing I^{131} and the use of this material to determine plasma volumes. Since then considerable literature has accumulated on this subject and RISA has been made commercially available. Gray and Frank (1953b) showed that $Cr^{51}Cl_3$, which in serum was bound to the proteins and could not move into any cellular spaces, could be used to determine plasma volumes The values obtained by this method were in good agreement with those obtained by other methods.

Methods for the simultaneous determination of red-cell and plasma volumes have also been reported Berson and Yalow (1952) used K^{42} or P^{32} to label red cells and simultaneously injected the labeled cells and RISA into the subject. Analysis of the blood after the mixing time gave results from which could be obtained both plasma and red-cell volumes. Gray and Frank used Cr^{51} as Na_2CrO_4 and $CrCl_3$ simultaneously as described above to obtain cell volumes and plasma volumes in the same determination. In perfusion experiments, the transfused cells were accounted for within 0.3 per cent and transfused plasma within 0.5 per cent.

Cardiac Output. An excellent review of all methods used for the determination of cardiac output has been given by Dow (1956). Earlier methods involved measurements of blood activity after their removal from the body of the subject. More recently Mack and Wells *(1955) and Pritchard, MacIntyre,* and Moir (1955) described methods using external counting for obtaining measurements of cardiac output. Both sets of authors inject RISA into the antecubital vein. By using a directional scintillation counter, properly attached to a graphic recorder and pointed at a large arterial vessel or over the heart itself, they obtained a tracing of activity against time. The cardiac output is calculated from an analysis of this curve. The results so obtained are reported as agreeing well with the classical method using helium gas.

Therapeutic Uses of Radioactive Isotopes. Jaffe (1953) reported on the use of I^{131} in euthyroid patients with severe cardiac disease. One hundred cases were followed for 24 months of therapy. No evidence of bone marrow depression, radiation sickness, thyroiditis, or temporary hyperthyroidism was noted when multiple small doses of I^{131} were administered

eraged 24 sec in health. Unfortunately, this method led to complications in patients with circulatory failure by causing severe reactions

Decholin Method (arm-to-tongue time). Winternitz et al. (1932) introduced sodium dehydrocholate (Decholin), 5 ml of a 20 per cent solution of this substance being injected into an antecubital vein It signaled its arrival in the capillaries of the tongue by the production of a bitter taste and an involuntary facial grimace With this method, Tarr et al studied extensively the various pathological states and found the arm-to-tongue circulation time to vary from 10 to 16 sec.

Saccharin Method (arm-to-tongue time) Fishberg, Hitzig, and King devised a less costly method by using saccharin They dissolved 2 5 Gm of soluble saccharin (sodium benzosulfimide) in 2 ml of distilled water, and heated the mixture just long enough to dissolve the saccharin The end point was a sweet taste. The normal circulation varied between 9 and 16 sec A disinclination to accept this method is attributable to the venous thromboses which develop in certain cases

Calcium and Magnesium Salts (arm-to-tongue time). Goldberg (1936), and later Bernstein and Simkins, introduced the calcium gluconate method as a means of measuring the circulation time from the antecubital vein to the capillaries of the tongue and face Three or five milliliters of 20 per cent solution or 6 ml of a 10 per cent solution of calcium gluconate was injected into an antecubital vein and a sensation of heat in the tongue and pharynx or face served as the end point with a mean average of 12 5 sec The normal arm-to-tongue time was 7 to 17 sec. A calcium and magnesium mixture was employed by Spier et al, who introduced a procedure for the coincident determination of circulation time from the antecubital vein through the vascular system, notably to the tongue, each hand, and each foot They injected 2 ml of a solution containing 42 Gm of magnesium sulfate in 100 ml of distilled water The arrival of this solution was evidenced by a sensation of heat The average circulation time to the tongue was 14 6 sec, to the hands, 26 sec, and to the feet, 28 sec

Sodium Cyanide Method (arm-to-carotid-sinus time) Robb and Weiss (1933) employed the carotid sinus stimulation by sodium cyanide as a means of measuring the circulation time A 2 per cent solution of sodium cyanide (optimum dose = 11 mg/kg) was administered through the antecubital vein The end point was a sudden reflex deepening of respiration which can be observed or recorded graphically. The average normal circulation time (arm-to-carotid-sinus time) determined by this method is 15 6 sec (range 9 to 21 sec)

Alpha Lobeline Method (arm-to-medulla time). Berliner (1940) attempted to popularize alpha lobeline[1] as a safe and objective method for measuring the arm-to-medulla time. The end point following the injection of 0 5 ml of 1 per cent solution was cough, usually with a grimace and hyperpnea. The average normal time was 11 to 12 sec Alpha lobeline, however, was found unsuitable for studying circulation time because it is an alkaloid with an undetermined seat of action and unpleasant side reactions

Sodium Succinate Method (arm-to-throat time). Greenfield (1950) injected 1 5 ml of a 30 per cent aqueous solution of disodium succinate hexahydrate The end point was identified by an elevation of the cricoid cartilage, choking sensations and cough The normal arm-to-throat time was 12 to 19 sec with a mean normal value of 15 sec Although this method is satisfactory, it does not compare well with the subjective methods of Decholin, saccharin, and calcium, in which the subjective end points have sharper and earlier signal reactions

Sodium Fluorescein or Riboflavin Methods (arm-to-conjunctiva time, arm-to-lip time). Fractional circulation times with fluorescent tracer substances such as sodium fluorescein or riboflavin were used by Windsor et al (1947) Two milliliters of a 20 per cent solution or 3 ml of a 15 per cent solution of sodium fluorescein (or 0 8 mg/kg of riboflavin) was injected into an antecubital vein. The measurements of 10 to 16 sec as normal compare to those found with Decholin, saccharin, and calcium Fluorescein or riboflavin measure the arm-to-lip or the arm-to-conjunctiva time depending upon which site is chosen for the registration of the end point. This excellent objective method requires a dark room as well as a source of ultraviolet light (for example, a carbon-arc glow lamp with a heat-resisting purple filter). A recent modification using the histamine wheal permits sharper visualization of the fluorescent end points at desirable locations in different portions of the body.

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Intra-sul Method (arm-to-lung time; arm-to-tongue time). Hodas and Cucci (1956) introduced a method for the simultaneous determination of systemic and pulmonary circulation times They

[1] This test had been previously suggested by Teplov and Sor.

of the substance employed in the test and on the sensitivity and speed of response, or lag, of the detecting instrument (*objective method*), or on the reaction time (*subjective method*) of the individual tested.

A more inclusive definition would regard circulation time as *that measured time interval during which the fastest signal-bearing portion of a substance injected into a vein travels the shortest pathway in the circulatory system through the lungs to reach a designated site on the arterial side where it produces its characteristic physiological or physical response.*

Circulation time is not only intimately related to the cardiac output and the circulating blood volume but is one of the most important of the three circulatory variables that participate in the maintenance of the dynamic circulatory equilibrium of the organism as a whole The quantitative interrelationships may be expressed as follows.

$$CT = K(CBV\ CO)$$

where CT = circulation time
CBV = circulating blood volume
CO = cardiac output per minute
K = a constant

Constant K is complex and influenced by a multitude of factors which may change, not *only in different individuals, but even in the* same individual under varying conditions

In accordance with the above formula, the circulation time will vary with the above-mentioned basic circulatory variables Its accuracy, assuming other factors are controlled, involves homeostatic mechanisms which operate to restore the cardiac output to a level that will satisfy the metabolic needs of the tissues whenever physiological or pathological conditions arise to either increase or lower that output

HISTORY

The earliest knowledge of the velocity of blood flow dates back to Harvey. Hering (1829) made the first measurement by injecting potassium ferrocyanide into one jugular vein of a horse and determining the time of appearance of Prussian blue in samples of blood withdrawn from the opposite jugular vein His average reading for this measurement was 26 2 sec Volkmann (1850) built *the hemodromometer*, a device which gaged the velocity of flow through displacement of a pendulum inserted into the lumen of a blood vessel. Vierordt (1858) duplicated Hering's work and improved on it with a new *hemotachometer.* He noted that the velocity of blood flow was inversely proportional to the size of the animal and directly proportional to the pulse rate.

Renewed interest in the problem of blood flow velocity was initiated by the studies of Stewart (1894). He estimated the circulation time and the cardiac output in dogs by injecting a hypertonic solution of sodium chloride into the right ventricle and determining the end point by means of a Wheatstone bridge. He also employed methylene blue and observed its arrival time in the common carotid artery.

The first determination of the circulation time in man was carried out by Koch (1922) He injected a solution of fluorescein into an antecubital vein and, by withdrawing successive samples of blood from the other antecubital vein, determined the time required for this substance to pass from one arm vein to the other. Koch found that, in healthy adults, the arm-to-tongue circulation time varied between 12 and 26 sec with an average of about 20 sec, and that this value tended to be lower in young individuals.

METHODS

***Radium Emanation Method* (*arm-to-heart time; crude pulmonary time*).** The first real advance in the study of the blood velocity was made by Blumgart and Yens. They injected radium C into an antecubital vein and, by means of a suitable detecting apparatus, observed the time required for the radium deposit to reach the right heart (arm-to-heart time) and further, the time required for the substance to travel from the right heart to the arteries of the opposite arm, they termed this the crude pulmonary circulation time. With the radium method, Blumgart and Weiss found that, in health, the circulation time from the antecubital vein to the opposite antecubital arteries varied from 12 to 24 sec in different individuals, with an average of 18 sec The arm-to-heart time ranged between 2 and 14 sec, with an average of 6 6 sec *They found that the crude* pulmonary circulation time varied between 5 and 17 sec, the average being 10 8 sec

***Histamine Method* (*arm-to-face time*).** Weiss, Robb, and Blumgart (1929) injected into an antecubital vein a 1 5,000 or 1.10,000 solution of histamine phosphate, an amount equal to 0 001 mg/kg of body weight. Histamine, which measured the arm-to-face time, signaled its arrival in the minute facial vessels by flushing the face and inducing a peculiar metallic taste in the tongue The arm-to-face circulation time by this method av-

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injected 4 ml of *Intra-sul*, a substance that has been used in the treatment of arthritis, and obtained readings with this method comparable to the ether and Decholin times. A smell reaction (sulfur) gave the arm-to-lung time a mean value of 7.1 sec (compared with 6.9 sec for ether), and a metallic taste at 11.6 sec gave the arm-to-tongue time (compared with 11.5 sec for Decholin). This method has the advantage that both the arm-to-lung and the arm-to-tongue times may be estimated by means of a single intravenous injection.

TABLE 4-10. CIRCULATION-TIME DETERMINATIONS

Signal substance	*Signal site*	*Signal reaction*	*Normal circulation time, sec*	*Method used by*
SUBJECTIVE TESTS				
Decholin	Tongue	Bitter taste	10.0–16.0	Winternitz, Deutsch, and Brull, 1931
Calcium gluconate	Tongue	Hot sensation	10.0–16.0 (12.4 avg)	Goldberg, 1936
Magnesium sulfate	Tongue	Hot sensation	10.0–20.8 (11.4 avg)	Bernstein and Simkins, 1939
Magnesium sulfate, comp (Macasol)	Tongue Hands Feet	Hot sensation	14.6 avg 26.0 28.0	Spier, Wright, and Saylor, 1936
Saccharin	Tongue	Sweet taste	9.0–16.0 (12.5 avg)	Fishberg, Hitzig, and King, 1933
Thiamine	Tongue, nose	Hot sensation	5.0–13.0	Ruskin and Decherd, 1945
OBJECTIVE TESTS				
Fluorescein	Mucosa or conjunctiva	Fluorescence	12.0–26.0 7.0–15.6	Windsor, Adolph, Ralston, and Leiby, 1947
α-Lobeline	Throat	Cough	6.0–13.0	Berliner, 1940
Radioactive sodium	Other arm	Radioactivity	11.0 avg (children) 7.0 avg (infants)	Hubbard, Preston, and Ross, 1942
Papaverine	Medulla	Sudden deep respiration	15.4–27.0 (20.8 avg)	Elek and Solarz, 1942
Diodrast	Left ventricle	Radiopacity	6.0–9.0	Robb and Steinberg, 1939
Methylene blue	Skin	Photoelectric cell determination: diminution in oxygen saturation	7.0–21.6	Jablons, Cohen, and Swirsky, 1944
Sodium succinate	Throat	Cough	12.0–19.0 (15.0 avg)	Greenfield, 1950
Intra-sul	Lung Tongue *	Smell Metallic taste *	7.1 avg 11.6 avg	Hodas and Cucci, 1956
Ether	Nose	Smell	4.0–8.0	Hitzig, 1935
Carbon dioxide (inhalation)	Carotid sinus	Deep respiration	5.0–10.0	Gubner, Schnur, and Crawford, 1939
Helium or nitrogen with oximeter (inhalation)	Ear	Photoelectric cell determination diminution in oxygen saturation	4.1–7.0	Wexler and Whittenberger, 1946

* Subjective reaction reported by patient

METHODS FOR THE SEGMENTAL STUDIES OF THE CIRCULATORY PATHWAY THROUGH THE LUNGS

Since the early work of Blumgart et al. and of Robb and Weiss, many methods have been recommended for measuring the circulation time in various arbitrary segments of the circulation.

Scientific curiosity suggested the use of circulation-time methods for the greater understanding of the hemodynamics of peripheral vascular disease. This encouraged investigators to employ mixtures of magnesium, calcium, and sodium in order to measure blood flow in different portions of the systemic arterial circulation. Similarly, fractional fluorescent tracer substances (fluorescein and riboflavin) were injected, and the registration of fluorescence in previously prepared histamine wheals denoted circulation times in these specially designated areas supplied by the systemic arterial capillaries.

Ether Method (arm-to-lung time). The ether method, an objective as well as a subjective method, has proved itself clinically applicable for measuring the pathway of the right heart unit. The principle of the method involves the intravenous introduction of a volatile substance (ether or paraldehyde), and the measurement of the time that elapses before the odor characteristic of the injected substance is perceived by either patient or investigator. During this time interval the foreign substance passes through the peripheral venous segment, the right heart, and the pulmonary artery to the pulmonary arterial capillaries whence it volatilizes into the pulmonary alveoli. It then ascends with great rapidity through the air passages to the olfactory organ and is readily recognized. With this method, 5 minims of ether mixed with 10 minims of normal saline solution, when injected intravenously, led to a facial grimace combined with a cough and an ether taste or smell as the end point yielding a normal arm-to-lung time of 4 to 8 sec. Among the volatile substances available for measuring the circulation time from the antecubital veins to the pulmonary capillaries, ether is the most satisfactory for the following reasons:

1. Its volatility at blood temperature is so great (ether boils at about 35°C) that when even a small quantity is injected, the amount that volatilizes in the pulmonary capillaries during the first circuit of the blood is invariably sufficient to be perceptible by smell.
2. Only a small volume is needed.
3. It gives no constitutional symptoms in the quantities used.
4. Because of its marked volatility, the measurement can be repeated as often as desired.
5. Paravenous infiltration causes no necrosis.

Although ether has certain advantages, it is still not the ideal substance.

Carbon Dioxide Method (lung-to-carotid-sinus time). Direct methods of measuring the lung-to-carotid-sinus time include the CO_2 inhalation method, first described by Bornstein (1912) and improved by Gubner et al. It obviates intravenous injections, but the fact that two breaths of 50 per cent CO_2 are necessary raises the question as to the correct starting time for the registration of the time interval, the end point being respiratory stimulation (acceleration and deepening) with simultaneous flushing of the face. The lung-to-carotid-sinus time is 5 to 10 sec. Since the end point is not always sharp, concentrations less than 50 per cent invariably give different values for the circulation time.

Nitrogen or Helium Method with Oximeter (lung-to-ear time). Similar measurements may be obtained by employing the oximeter which registers a decrease in arterial oxygen saturation after one inhalation of 100 per cent nitrogen or helium. In this way, a direct measurement of lung-to-ear time (pulmonary-to-systemic-capillary time) is obtained as a measure of left heart function. The end point is a reduction in arterial oxygen saturation at the site of the oximeter. The lung-to-ear time thus obtained measures from 4.1 to 7 sec in normal subjects. By subtracting the lung-to-ear time from the arm-to-tongue time or from the arm-to-ear time (by using the oximeter-dye method), the arm-to-lung time could also be obtained by an indirect method.

This direct measurement of the pulmonary-to-systemic-capillary circulation time is of great value in corroborating the measurement of the lung-to-tongue time with Decholin and ether and also in aiding the understanding of the dynamics of left ventricular failure.

OBJECTIVE VERSUS SUBJECTIVE METHODS

Since the concept of circulation time was first established, a huge quantity of literature has been published and a variety of substances has been advocated, each with a preferential claim of superiority over its predecessors. Among the universal claims that the substances used are nontoxic, can be used in small quantity, and can be repeated at random because they are readily eliminated, there is occasionally one advantage that is featured, namely, that the signal reaction, or end point, of that particular substance is entirely objective.

Among cardiologists, who employ this simple circulatory adjuvant of circulation time either in differential diagnosis or in determining the extent of myocardial insufficiency, this problem of choice of methods arises not infrequently. Students who are engaged actively in problems of the circulation favor the subjective over the objective method, except in certain instances, such as in catheterization techniques or in testing unconscious or uncooperative patients, where no alternative is left in the choice of method.

Although early methods which led to the pioneer observations of the velocity of blood flow were almost entirely objective, the vast group of newly proposed substances, with the exception of the radioisotopes, has been mainly subjective with respect to end point. Apparently what determines whether signal reactions are either subjective or objective is closely related to the physical and pharmacological characteristics of the substances injected. For example, methods that have utilized the physical properties of substances such as fluorescein and hypertonic sodium chloride solution, radium emanation and, more recently, the radioisotopes, are mainly objective, whereas those substances that evoke a specific pharmacological or physiological response are either subjective (calcium chloride, calcium gluconate, sodium dehydrocholate, saccharin, and magnesium) or purely objective (carbon dioxide, histamine, and sodium cyanide)

The claims of relative merit of the subjective versus the objective methods deserve further evaluation. Theoretically, an objective method in which factors of subjectivity are totally excluded should give a more accurate reading In such instances, the subject does not have to be briefed and his complete cooperation is not necessary The advantages are obvious when such methods are applied to the comatose subject and to the patient suffering from peripheral shock, in both of which conscious cooperation of the individual is often negligible Except in these isolated instances, actual experience with both of these methods over a period of years reveals that greater authenticity is attributable to the subjective rather than to the objective method. When a sweet or bitter substance is injected into a peripheral vein and the time elapsing between the injection and the arrival of the substance at another point in the circulation is recorded, one cannot doubt that it actually did reach the designated signal area. A comparison of both methods by using substances which are either objective or subjective has been sufficiently conclusive to state unmistakably that shorter circulation times are more frequently obtained with the subjective method, especially when measuring the entire pulmonary pathway. In some objective methods that require cumbersome instruments, the mechanical lag may actually occupy a considerable portion of the recorded circulation time This was especially true of the pioneer radium emanation method. It is certainly not true of the oximeter nitrogen inhalation method of measuring lung-to-ear time. It is impossible to say whether similar criticism could be extended to the radioactive isotopes now employed experimentally in the study of the velocity of blood flow, such as radioactive sodium, in which a Geiger-Muller counter is necessary to register the earliest arrival of the radioactive factor.

In some objective methods, a coexisting end point may at times impart helpful subjective corroboration. The flush of histamine, for instance, is confirmed by the associated dyspnea which develops simultaneously after its arrival in the facial arterial capillaries, a dyspnea which is not disturbing in normal subjects but which contraindicates its use in victims of cardiac disease. Similarly, when the *ether method* is used, ether, which is volatilized in the lung, yields an end point which is either objective (if the ether smell is detected only by the inhaling investigator situated near the subject), or entirely subjective (when it is detected by the subject under study).

THE METHOD OF DETERMINING THE CIRCULATION TIME

Before embarking on a method of determining the circulation time through the lungs, the investigator must decide on the nature of the information he is seeking. Does he wish to establish that the patient has a normal circulation, or that he may be in heart failure? If he has heart failure, does it involve both the right and left sides of the heart? Is the asthma on a bronchogenic or cardiogenic basis? If the right heart is still functionally compensated, as judged by a normal venous pressure curve, is this a true case of isolated left ventricular fail-

ure? If he is concerned about the patient's clubbed fingers, which in the presence of a heart murmur and pulmonary abnormalities [illegible]

[illegible] left shunt for which an abbreviated arm-to-tongue time or an arm-to-paresthesia time might provide corroborative *information*? Will he then repeat the ether method to confirm the ether paresthesia time, a pathognomonic *finding characteristic* of right-to-left shunt, and thus give credence to the abbreviated circulation time with either Decholin, saccharin, or calcium?

When a decision has been made as to the necessary information to be obtained, the investigator chooses the appropriate substance to record the arm-to-lung and arm-to-tongue times, as well as the arm-to-paresthesia time (with ether, if congenital heart disease is present) *If he has adequate facilities, he can also* establish directly the lung-to-carotid-sinus time with carbon dioxide or the lung-to-ear time with helium and the oximeter, instead of using the indirect method of subtracting the arm-to-lung time from the arm-to-tongue time in order to obtain by the indirect method the comparable lung-to-tongue time He can even combine with a single injection of Intra-sul (a recent method of equivocal efficiency in cases with marked prolongation of circulation time) the registration of both the arm-to-lung and arm-to-tongue times from which the lung-to-tongue time can be *similarly obtained*

The clinical methods which lend themselves most readily to the measurement of the arm-to-tongue time are substances that register a subjective end point (bitter, sweet, warm) and these have stood the test of time They are Decholin, saccharin, or calcium gluconate Despite their subjective end points, they have proved themselves to be no less accurate than the objective methods, a fact which even the objectivists will *not deny* since in most instances when both methods have been used for comparative purposes, the subjective method has yielded the shorter circulation time This should be sufficient proof that, despite the time of the psychomotor reaction of the patient, the time of the psychomotor reaction of the observer who is recording the time, and the problem of full cooperation of the patient, the subjective method carries greater veracity than the objective method in most instances.

The test should be performed under basal conditions, after the patient has rested in a recumbent position for at least 20 min After briefing the patient about *the nature of the test*, he should be reassured that no discomfort will be associated with its performance. While the subject reclines comfortably in bed or on the examining table, his arm is propped up to a level corresponding to the right atrium. He is then instructed not to hold his breath but to breathe normally after the needle is inserted, since *breath-holding may retard* the venous return to the heart. Depending upon the nature of the substance to be used, he is acquainted with the end point as follows:

Decholin a bitter taste (arm-to-tongue time)
Saccharin a sweet taste (arm-to-tongue time)
Calcium a warm or hot sensation of the throat or pharynx (arm-to-tongue time)
Ether· a smell of ether (arm-to-lung time)

It is important to emphasize that the patient must announce the end point immediately when it arrives by saying either· "sweet," "bitter," or "hot" After the tourniquet has been applied, a needle with a large bore, preferably 18 gage, is introduced into the vein After waiting about 30 sec for the release of the tourniquet to allow local circulatory disturbances to subside, the investigator rapidly injects the mixture, taking only a fraction of a second for the procedure. A stop watch is started the instant the injection is begun and stopped when the patient signals the end point or when an objective end point is noted The end point should be sharp and unmistakable In the case of ether, the investigator can place himself in a position *close to the subject* to perceive the ether odor almost as rapidly as the patient Objective confirmation, valuable as it is in itself, becomes of especial importance when studying unconscious or uncooperative patients The time interval that elapses between the injection of a substance and the registration of the end point is clocked and represents the circulation *time of the pathway of either the* right heart unit (arm-to-lung time) or of the total circulation from the arm through the lungs, to the systemic arterial capillaries (arm-to-tongue time). Whenever possible, the test should be repeated after a few minutes to check the results.

In cases of superior vena cava syndrome, the ether, Decholin, calcium, or saccharin circulation time may be of value if carried out from the veins of the lower extremity, either from a dorsal ankle vein or even from the femoral vein. The procedure is essentially *the same* The extremity with the chosen vein is raised to the level of the right atrium If the veins of the ankle are employed,

their small caliber may require that a hypodermic rather than a larger needle be utilized for the injection. Other substances that have been mentioned above may be similarly employed. The substance that is used for this purpose must fulfill the following requirements:

1. The substance should be nontoxic in the dose utilized.
2. The substance should not be previously present in the body.
3. The substance should not have any undesirable effects upon the condition under study.
4. The unpleasant side effects should be minimal.
5. The substance should be rapidly eliminated or destroyed in the body so that the determination can be rapidly repeated.
6. The substance should have an end point which is clear to the subject, if it is subjective, or to the investigator, if it is objective.

Although the methods that employ these substances have wide clinical applicability, they present certain limitations which must always be borne in mind. In the first place, the arm-to-heart time is not as a rule accurate because if the injected substance is large in quantity the extra push will cause an abbreviation of this brief time interval. Moreover, the circulation time does not really measure a complete circuit, since the foreign substance is injected into a medium-sized vein and the subjacent portion of the vein distal to the heart, as well as its venous capillaries, are not included, which makes the circuit incomplete. Actual doubt is raised as to whether the values obtained with physical or biochemical methods really represent the true velocity of blood flow, since the reaction time in such methods,

TABLE 4-11 CHARACTERISTIC CIRCULATION TIMES, IN SECONDS

(Average readings)

	Arm-to-lung time	*Arm-to-tongue time*	*Lung-to-tongue time*
Normal individuals	3-8	9-16	5.5-10
In cardiovascular conditions			
Left heart failure (rare type)	5-8	13-16	8-10
Left heart failure (severe), isolated	5-8	20-40	12-32
Left heart failure with "incipient" right heart failure	10-16	25-50	15-34
Left heart failure with secondary right heart	10-18	25-50 (rarely up to 60)	17-36
[illegible]	10-14	16-26	6-10
[illegible] heart [illegible]	12-16	18-32	12-16
Shock (peripheral failure)	10-12	18-30	8-18
Coronary occlusion with normal dynamics	3-8	12-16	5.5-10
Coronary occlusion with heart failure and shock (due to low output)	8-10	24-40	16-32
Superior vena cava occlusion:			
Above azygos vein	6-9	12-18	5.5-10
Below azygos vein	10-12	14-22	5.5-10
Myxedema	6-8	12-16	6-10
[illegible]	8-12	18-24	8-12
Polycythemia	8-10	16-22	8-12
[illegible]	4-7	7-13	5-8
[illegible]	7-14	24-32	16-22
[illegible]	3-6	6-9	3-4
[illegible]	3-5	6-8	3-4
[illegible] (unilateral)	3-6	7-10	4-7
Bronchial asthma	3-6	7-12	4-7
Beriberi (normal circulatory dynamics)	3-6	9-16	5.5-10
Beriberi (high output)	3-6	7-11	4-8

especially in the subjective methods, may not be more than just a negligible fraction of the total circulation time.

This point is especially emphasized by the abbreviated roentgen circulation times which have been observed *by Sussman et al*, *and* Robb and Steinberg, who used concentrated Diodrast for contrast visualization of the heart and great vessels. The rapidity of blood flow as observed in subjects when they are in the erect *position behind* the fluoroscope has created doubt as to the fidelity of the circulation-time methods in bedside medicine inasmuch as roentgen times are shorter when compared with standard subjective or objective methods executed in recumbency. It must be remembered that direct visualization of the Diodrast mixture *under the fluoroscope serves* as the end point and that the visualization site is proximal to the arterial capillaries, unlike other circulation-time techniques where the injected substance travels to the very periphery *in order* to evoke the specific response Since the end points in roentgen circulation times carried out *in the erect position depend mainly* on direct visualization in the larger blood vessels, their brevity offers no basis for comparison, since in the standard techniques, carried out in recumbency, there is in addition to the arterial capillary flow, the reaction time of the subject under investigation (when the method *is subjective*) *or the mechanical* lag of the instrument (when the method is objective).

ABBREVIATION OF *CIRCULATION TIME*

Physiological Conditions Associated with Abbreviated Circulation Time. The circulation time *is shortened under certain* physiological conditions It is for this reason that, whenever circulation time tests are necessary, they should be performed under strictly basal conditions. For example, they must not be carried out during digestion and after exercise, since the cardiac output *increases during these* conditions and consequently *the* circulation time may be reduced During periods of great mental *and emotional stress*, when the pulse rate accelerates beyond a certain optimum range, the circulation time may become proportionately decreased to a degree which bears an inverse relationship to the acceleration of the pulse. Hyperventilation, whether *it is* emo-

ing febrile states in which cardiovascular function is intact, the circulation time *is also decreased* as a result of the increase in oxidative metabolism with consequent peripheral vaso-*dilatation, the extent* of reduction being inversely proportional to the height of the fever.

Sh

of the blood with elimination of the pulmonary pathway. As a consequence there is shortening of the time a tracer *substance travels from* a peripheral vein to the systemic arterial capillaries.

2. Anemia.
3. Hyperthyroidism.
4. Acute and chronic *pulmonary insufficiency* (cor pulmonale).
5. Arteriovenous fistula.
6. Pregnancy.
7. Beriberi heart disease.

PROLONGATION OF THE CIRCULATION TIME

Prolongation of the circulation time occurs in a variety of pathological conditions.

1 *Congestive heart failure*

a. Initiated by diseases *which dominantly* affect the left side of the heart leading first to its functional insufficiency; eventually, depending upon the passage of time and factors of overwork, this ends in secondary right heart failure (as seen *in hypertensive, arteriosclerotic, rheumatic*, and luetic heart diseases).

b Initiated by pulmonary diseases in which the functional alteration in ventilation and aeration leads to arterial hypoxia, increased pulmonary vascular resistance and eventual hypertension of the *pulmonary circuit*, and ends in primary right heart failure (primary right heart failure or decompensated stage of cor pulmonale). In rare instances, pulmonary hypoxia, by causing coronary insufficiency, exercises a deleterious *effect on* the myocardium of the left ventricle, end-*ing in secondary left* heart failure.

2. *Polycythemia vera*
3. *Myxedema*

Compensated cardiovalvular and cardiovascular disease may be accompanied by normal circulation times. On rare occasions, cases of frank congestive heart failure have come under the author's observation in which circulation times were within the normal range but no evidence of the possible coexistence of masked high output failure (anemia, arteriovenous fistula, etc.) was ever found. Tachycardia was present in some of these cases but, although masked hyperthyroidism was most often considered in the differential diagnosis, laboratory investigations failed to substantiate its possible presence. On the other hand, there have been occasional cases of presumably normal people in whom the measured circulation time was prolonged. In these instances, careful clinical *and laboratory investigation did subsequently* establish on either a subjective or an objective basis that cardiac failure did coexist, but in a masked clinical state, in these individuals.

RADIOCARDIOGRAPHY

Prinzmetal et al. have described the radiocardiogram as a graphic record of the passage through the heart of a radioactive substance rapidly administered by vein, detected by a properly collimated counter placed over the precordium, and measured by a count rate meter (Fig. 4-83)

Blumgart and Weiss (1927) were the first to use a radioactive substance in order to measure the circulation time in man; their method can be considered the forerunner of radiocardiography. Prinzmetal et al. (1949) obtained significant records and made a good clinical evaluation of the method Subsequent technical refinements of the method, and a mathematical evaluation of the records and of their possible hemodynamic value, have been presented by Waser and Huntziger, Luisada et al, Veall et al, Shipley et al, and Gallini et al.

METHOD

A tracer emitting a sufficient quantity of gamma rays must be used Prinzmetal et al. made their first experiments with tagged *sodium chloride* (Na^{24}), a salt which has a very short half life,[2] costs very little, and spreads rapidly into the tissues. It was subsequently replaced by *serum albumin tagged with iodine* (Pritchard and McIntyre). Today *human serum albumin tagged with* I^{131} is considered the most suitable tracer for radiocardiography, because it does not diffuse through the pulmonary vessels and, having a half life of 8 days, is harmless.

Methane iodide (a gaseous substance) has been used by Gigli et al. for recording radiocardiograms of the left heart. The same authors further injected Au^{198} adsorbed on coal particles (which are blocked at the level of pulmonary capillaries) and obtained a *radio*-cardiogram of the right heart.

The optimal quantity of the isotope to be injected should be determined by evaluation of the sensitivity and shielding of the counter and the distance of this counter from the heart (obesity or pulmonary emphysema should be taken into consideration), and standardization of the counter and the recorder.

The dose varies from 5 microcuries (Shipley et al.) to 200 microcuries (Gigli et al.).[3] As

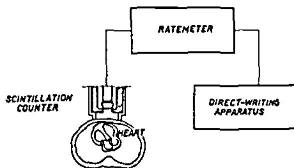


Fig. 4-83. Schematic presentation of the technique of radiocardiography. The radioactive substance flowing through the heart emits rays, which are detected by the scintillation counter, measured by the rate meter, and recorded by the direct-writing apparatus.

[2] *Effective half life of a radioisotope* is the time by which radioactivity in the body is decreased by one-half. Radioisotopes with a long half life are dangerous for the patient. On the other hand, radioisotopes with a too short half life are inadequate for radiocardiography because their radioactivity decreases too much before one gets them from the center where they are produced. The half life of I^{131} is 8 days and therefore seems the most suitable (see Chap. 5).

[3] Protection against radioactive contamination should be effected according to the special rules established at the Seventh International Congress of Radiology (Copenhagen, 1953). In any case,

such doses are harmless, the radioisotope can be injected two or three times with no danger to the patient, *especially* if *one desires to observe* changes in the radiocardiogram. Today [illegible] tion counter, used first by Luisada [illegible]

[illegible] tube was obtained by Prinzmetal et al. [illegible] a layer of lead, except for a slit, in order to *avoid the influence of radioactivity* in other tissues. Later, various authors have preferred a circular orifice of different diameters, but no *standardization* has been established as yet. *The* authors believe that the best *records are* obtained by placing the counter at 4 to 6 cm from the anterior thoracic wall. Collimation of *the counter should include* right as well as left chambers of the heart; this is easily done by positioning the counter on the center of the image obtained by *fluoroscopy.* Usually this *point coincides* with position 3 of the chest leads for electrocardiography.

Procedure of Injection. This is important in *order to obtain a good radiocardiogram.* In order to prevent excessive dilution of the radioactive substance injected, *one* should observe the following rules: (1) The *volume of the substance to be injected* should be small (0 3 to *1.0* ml). (2) The injection should be performed as rapidly as possible. (3) The needle should be of large gage (4) *The arm of the patient should have* been previously warmed and should be raised vertically immediately after the injection (5) The patient *must* be relaxed and calm, *preferably in a sitting position.* Cigh *et al. inject* the substance in the jugular vein of the patient during deep inspiration

According to the *authors' experience,* the recorder *should* have a film speed of 1 cm/sec It is advisable to register an electrocardiogram simultaneously

THE NORMAL RADIOCARDIOGRAM

As has been previously stated, the radiocardiogram indicates the concentration *of a radioisotope* within the *heart,** *correlated* with the time of injection.

Tracings of normal subjects (Fig. 4-84, Left) show two *principal waves:* the *first,* taller and faster, is caused by passage of the isotope through the right chambers of the heart (R *wave*); *the second* wave, lower and slower than the first, is due to passage of the isotope through the chambers of the left heart (L *wave*). The *two waves are connected* by a transitional deflection (T), which corresponds to the moment where the larger part of the radioisotope has left the right heart and has spread into the lungs.

The upstroke of the R wave is abrupt, almost vertical, and indicates arrival of the substance in the right heart. *Often, at the beginning of the R wave,* one can see a small wave which represents, according to Luisada et al., *arrival of the radioisotope* in the *right atrium.* The peak of the R wave is short and round, sometimes pointed, and represents the emptying *of the right atrium* (Cigh et al.). The downstroke of R represents emptying of the right ventricle, is longer than the ascending limb, and has a *more gentle inclination,* because *the* radioactive substance, following initial dilution in the peripheral veins (where it flows by layers) *and its mixing in the cardiac* chambers (turbulent flow), remains in the right heart for a longer time than that needed to enter it.

The L wave *is of smaller* amplitude and longer duration, shows a round peak, ascends and descends slowly. The form of the L wave is *determined by dilution of the tracer* in the large pulmonary bed, its slower backflow to the heart, and its mixing with the blood in the left heart chambers. The *upstroke of the* L *wave represents arrival* of the tracer in the left chambers of the heart; the downward slope corresponds to the outflow from the left ventricle.

The point of connection between the end of the L wave and a line of equilibrium above the base line is called E (emptying), *and indicates the end of the radiocardiogram.* After E, some *irregular* waves can be recorded and indicate

radiocardiography should be *performed only* in a well-equipped laboratory.

*Actually, the counter also *detects radiations* originating in tissues outside the *heart,* lungs, pulmonary vessels, mediastinum, large veins of the mediastinum, tissues of the thoracic walls, and even the myocardium. By means of various *technical* devices (short tracing, shielding, and *positioning* of the counter), these extraneous *radiations* can be minimized, so that it can be said *that the* radiocardiogram evaluates the *radioactivity* of the heart chambers.

recirculation of the radioactive substance through the greater and lesser circulations.

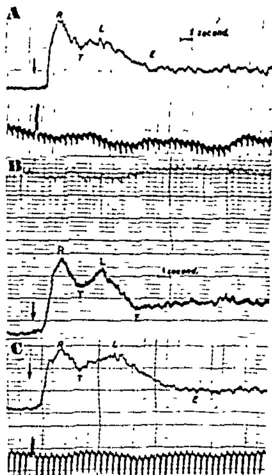
According to Waser and Huntziger, in half of the tracings one can record a small peak at the end of the L wave; this is due to intracardiac recirculation of radioactive substance, and could be used for *determination of the coronary circulation time.*

ANALYSIS OF A RADIOCARDIOGRAM

In evaluating a radiocardiogram, one should consider the duration, form, and surface of the waves, and the slope of the curves.

Time Measurements. (1) *Vein-to-right-heart time* is given by the interval between the beginning of the injection and the beginning of the R wave. (2) *Mean pulmonary circulation time* is given by the interval between the peak of the R wave and that of the L wave and is usually from 3 to 5.5 sec. (3) *Total duration of the radiocardiogram* is measured from the beginning of the R wave to the point *E*, and varies in normal subjects from 9 to 13 sec. Higher figures are obtained in old individuals, although they are clinically healthy. On the other hand, in certain clinical conditions like anemia or hyperthyroidism (Fig. 4-84B) one can obtain lower figures.

Form of the Waves. A radiocardiogram can be altered either in its entirety, in one of its waves, or in part of one. One must consider the level and form of the transitional zone (this becomes less evident and may even disappear in advanced congestive failure and in severe



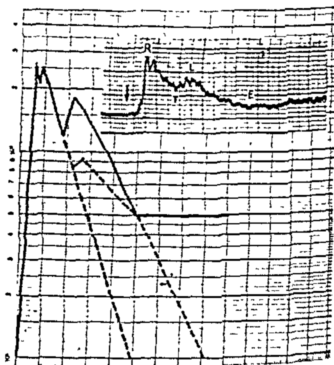


Fig. 4-84. (Left) A. Radiocardiogram, upper curve, of C R, 36 years old. Normal record. Lower curve, electrocardiogram. B. Radiocardiogram, lower curve, of O. B, 35 years old. Diagnosis, moderate hyperthyroidism. The duration of the curve is slightly shorter than normal. Upper record, electrocardiogram. C. Radiocardiogram, upper curve, of T. E, 62 years old. Senile record. The curve is slightly longer than normal. Lower curve, electrocardiogram. (Right) Semilogarithmic plot of a normal radiocardiographic curve. Upper right, normal radiocardiogram; lower left, its semilogarithmic plot. The descending limb of R has been extrapolated; an "absolute" L wave has been reconstructed as the difference between the actual L wave and the extrapolated R wave as indicated.

dilatation of the heart). Further, one should study the relationship between the R and L waves (e.g., one can observe a relative or absolute preponderance of L in aortic insufficiency and in hypertensive and arteriosclerotic heart disease) and especially the slope and duration of the ascending and descending limbs. It must be emphasized that only primary changes are significant, because variation of a part of the curve, secondary to changes in other waves, indicates a slowing of the tracer due to variation of flow in other chambers. This is why the radiocardiogram cannot show data on the flow of the left heart when the R wave is already altered by a condition of the right chambers or of the lungs For instance, in the case of venous engorgement due to right heart failure or constrictive pericarditis, the upstroke of the R wave ascends more gently, and changes in all other parts of the record must be considered as secondary to it.

From the measurements of the area and the downward slope of the waves, important data can be obtained in regard to cardiac output, ventricular diastolic volume, ventricular systolic residual blood, and volume of the blood contained in the pulmonary vascular bed. Calculation is based on the similarity of the curve obtained through radiocardiography with that obtained with injection of a dye, and is based on principles of dilution according to the studies of Stewart, Hamilton and Kinsman, and Newmann. These calculations can be effected if a semilogarithmic plotting of the curves of a well-recorded radiocardiogram is possible. The hidden part of the descending limb of the R wave must be extrapolated (Fig 4-84, Right), and the L wave is reconstructed as the differ-

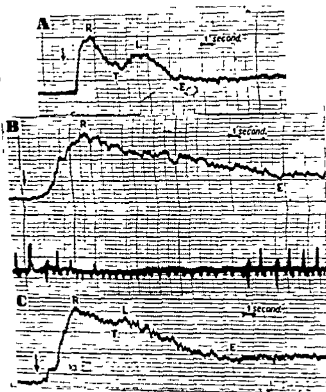


Fig. 4-85. A. Radiocardiogram of V. N, 34 years old. Diagnosis, rheumatic heart disease with pure *mitral stenosis*, clinically no evidence of heart failure. The plateau of L is probably due to pooling of the tracer in the enlarged left atrium B. Radiocardiogram, upper curve, of A L, 36 years old. Diagnosis, rheumatic heart disease with mitral stenosis and atrial fibrillation. The T deflection and L wave are indistinguishable. Lower curve, electrocardiogram C. Radiocardiogram of G A., 62 years old Diagnosis, chronic *cor pulmonale* with pneumoconiosis and emphysema. The downward slope of R is longer and descends gently because of slower emptying of the right heart.

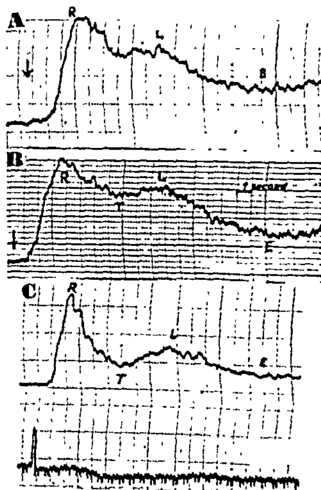


Fig. 4-86. A. Radiocardiogram of A. G., 68 years old. Diagnosis, *moderate arterial hypertension and diabetes.* The duration of the curve is slightly longer than normal. B. Radiocardiogram of V. M., 47 years old. Diagnosis, *old posterior myocardial infarction.* The morphology of the waves is normal, but their duration is longer (7 sec); the mean pulmonary circulation time is also longer. C. Radiocardiogram, upper curve, of B. C., 62 years old. Diagnosis, 40-day-old *myocardial infarction.* The R wave is normal. The ascending limb of L is longer than normal; so is the mean pulmonary circulation time.

ence from the former. In this way, "corrected" mean pulmonary circulation time is also determined. These mathematical calculations cannot always be made, especially for abnormal radiocardiograms, and may be subject to errors of evaluation. Besides, very little is known about the relationship between the hemodynamic measurements obtained from the radiocardiogram and those obtained by more traditional methods.[5]

[5] For greater details on quantitative radiocardiography see Veall, Shipley, Grandoinco et al., and Donato et al.

Computation of cardiac output from the radiocardiogram is given by the equation of Stewart.

$$F = \frac{Q}{Ct}$$

where F = cardiac output
Q = quantity of tracer
C = its mean concentration at the moment of the passage point
t = the duration of passage

Some authors think that, provided there is no diffusion of the tracer and there is a complete mixing of blood in the right heart, the denominator could be obtained from the area of the R wave.

The method of Huff et al. is more reliable. These investigators effect the computation from the curve obtained through positioning of the shielded counter on the left parasternal line between the first and the second ribs; in this way, they record the passage of the radioactive substance in the aortic arch.

The volume of blood contained in the pulmonary bed could be obtained by multiplying the value obtained for cardiac output by the pulmonary circulation time. The volume of blood contained in the right heart, according to Newmann, could be determined from the relationship between cardiac output and inclination of the downward limb of the R wave. The systolic residual blood in the ventricle could be obtained by deducting the volume of the blood in the right heart from the cardiac output.

According to Gigli et al., all these measurements can be obtained for the left heart by the use of radioactive methane iodide (see above).

CLINICAL APPLICATIONS

Even though greater technical refinements in quantitative radiocardiography are needed before its hemodynamic data can be widely used, the evaluation of a radiocardiogram from a morphological and chronological point of view offers data of practical importance, which can be used for diagnosis and evaluation of function.

No tracing can be considered specific for a particular heart disease. However, a few patterns are significant in certain conditions.

1. In *congenital heart disease* (Fig. 4-87C) with left-to-right shunt, the descending limb of the L wave drops very gradually as the flow of tagged substance recirculates in the right heart through the shunt.

2. In *chronic cor pulmonale* (Fig. 4-85C), the downward limit of the R wave is of longer

duration and descends more slowly, indicating a slower emptying of the right ventricle.

3. When *congestive heart failure* is present, the tracing reveals the altered hemodynamic condition but no data can be obtained about the type of heart disease.

4. In *right heart failure*, as well as in *constrictive pericarditis* (Fig. 4-57B) with venous stasis, the first limb of the R wave ascends very slowly, the R wave itself is of great amplitude and long duration, the T point is poorly distinguishable, and the L wave is of longer duration and undistinguishable.

5. *Right heart failure in cases of mitral disease with marked dilatation of the left atrium and atrial fibrillation* gives the most abnormal tracing with a single, long, monophasic curve (Fig. 4-55B).

6. In *left heart failure*, not yet complicated by a severe and prolonged hypertension of the pulmonary vessels, only the L wave is altered.

7. If the residual blood contained in the left ventricle is augmented, as in the first stage of systemic hypertension with initial left ventricular failure, the radiocardiogram shows moderate prolongation and lesser inclination of the descending limb of the L wave (Fig. 4-58A).

8. When the left ventricle and the left atrium are dilated, or the pulmonary veins are engorged, the ascending limb of the R wave is also of longer duration and less steep; consequently, the L wave becomes very large. Major degrees of these changes can be observed in aortic insufficiency (Fig. 4-57A), hypertensive heart disease, and coronary heart disease with dilatation of the left ventricle.

Therefore, radiocardiography offers useful data on the type and stage of heart failure (Gallini et al.) and can be particularly helpful in detecting slight hemodynamic changes in the early stages of certain pathological conditions, such as the initial ventricular strain of arterial hypertension, chronic bronchopulmonary diseases, coronary heart disease, and metabolic heart disease. In the case of myocardial

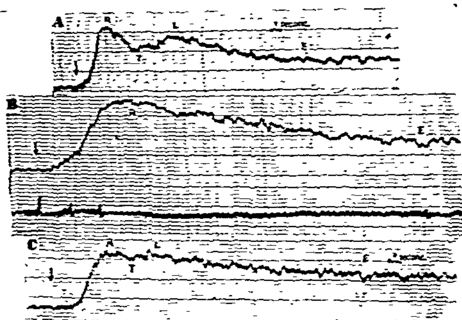


Fig. 4-57. A, Radiocardiogram of R. Z., 35 years old. Diagnosis, aortic insufficiency. Left ventricular strain in the electrocardiogram. The ascending limb of L is longer and the descending limb much longer, because of slower inflow and outflow of the enlarged left ventricle. B, Radiocardiogram, upper curve, of R. A., 45 years old. Diagnosis, chronic constrictive pericarditis. All parts of the radiocardiogram are elongated. The T deflection and the L wave cannot be recognized. Note the slowly ascending limb of R because of slow inflow of tracer in the right heart. Lower curve, electrocardiogram. C, Radiocardiogram of R. A., 21 years old. Diagnosis, atrial septal defect. The T deflection is poorly distinguishable; the downward slope of L descends very gently because of the left-to-right atrial shunt.

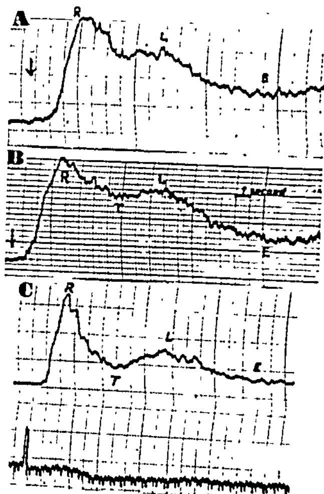


Fig. 4-86. A Radiocardiogram of A. G., 68 years old Diagnosis, moderate *arterial hypertension* and diabetes The duration of the curve is slightly longer than normal B. Radiocardiogram of V M., 47 years old. Diagnosis, *old posterior myocardial infarction* The morphology of the waves is normal, but their duration is longer (7 sec); the mean pulmonary circulation time is also longer C. Radiocardiogram, upper curve, of B C, 62 years old Diagnosis, 40-day-old *myocardial infarction* The R wave is normal. The ascending limb of L is longer than normal; so is the mean pulmonary circulation time.

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2. In *chronic cor pulmonale* (Fig. 4-85C), the downward limit of the R wave is of longer

put, identification of right-to-left and left-to-right shunts, and the immediate postcardiotomy assessment of the completeness of closure of intracardiac defects.

INDICATORS

Any substance to be used as an indicator in the circulation of human beings must meet special requirements, certain of which may be satisfied incompletely. (1) It must mix with the blood. (2) It must be identifiable in the blood (3) It must be nontoxic in the dose required for its use (4) It must be possible to sterilize the substance without destroying it. (5) It must be inert as a cause of circulatory reaction. (6) It should be retained completely within the vascular system. (7) It should dissolve in a volume sufficiently small to be injected rapidly via a long and narrow-bore catheter. (8) It should be stable in the blood stream and should not change its relation to the particular blood fraction which it is to tag. (9) Changes in the concentration of substances other than the indicator should not be recorded by the detecting instrument. (10) The dilution curve should be recorded as a continuous function. (11) The indicator substance should not change or deteriorate on storage.

Isotopic indicators, such as radioactive substances (albumin, sodium, or potassium) or erythrocytes or plasma (tagged with radioactive phosphorus or other substances) have not been used by the authors in the recording of arterial indicator-dilution curves. However, apart from differences regarding methods of detection, such dilution curves are similar to those discussed below if the indicator meets the requirements just listed

DYES IDENTIFIABLE SPECTROPHOTOMETRICALLY

Evans Blue (T-1824). This substance has been widely used for the determination of blood volume and is a dye of low toxicity which can be accurately quantitated either in whole blood or in plasma. The dose of this dye required for satisfactory dilution curves is determined chiefly by the sensitivity of the detecting instrument. Continuously recorded dilution curves of satisfactory amplitude can be obtained with an oximeter when doses of the order of 0 15 mg/kg of body weight are used. Doses of Evans blue of 0 5 mg/kg or more cause a bluish discoloration of the skin and membranes which interferes with the clinical evaluation of cyanosis and the determination of the oxygen saturation of blood by the oximeter. This is a serious disadvantage, particularly in certain of the more complicated forms of congenital heart disease in which a number of dilution curves are required for complete evaluation.

Methylene Blue. This substance is an aniline dye like T-1824. Although it does not cause discoloration of the skin, its rapid loss (by decolorization) from the circulation and the deviation which it exhibits from the Lambert-Beer law, complicate its application to quantitative studies. However, methylene blue used in dosage similar to that of T-1824 has some application as an indicator in diagnostic cardiac catheterization (Fox and Wood).

Indigo Carmine. This dye produces dilution curves closely similar in contour to those produced by Evans blue and does not cause discoloration of the skin (Lacy et al, 1955). However, the dosage required for continuous recording of dilution curves by an oximeter is about three times that of Evans blue, and because indigo carmine solutions cannot be prepared in concentrations greater than 0 8 per cent, a relatively large volume, 3 to 5 ml, must be injected for recording of dilution curves in adult patients. Such volumes are an obstacle to rapid injection via small catheters.

SAMPLING METHODS

Discontinuous. In the method described and used by Hamilton et al., blood was collected at intervals of 1 or 2 sec in a series of tubes as it flowed from a needle in the brachial or femoral artery The blood in each tube was then centrifuged and the concentration of dye determined spectrophotometrically in the supernatant plasma

Continuous. Current methods of sampling involve the continuous recording of concentration by detectors of several different types. The continuous method was first used by Stewart (1897) who recorded the changes in electrical conductivity across an artery when an injection of saline solution was made at a point upstream from the site of detection. The continuous recording of concentration of indicators is usually accomplished at present by means of oximeters, densitometers, or radioactivity counters Since the material to be discussed is based on extensive experience with dilution curves of T-1824 recorded by means of cuvette and ear oximeters, the principle of these instruments will be briefly described.

The whole-blood cuvette oximeter consists of a source of light and detecting photoelectric cells between which a polyethylene tube of uniform lumen and small volume is interposed (Fig 4-89). The optical density of the contents of the polyethylene tube determines the amount of light reaching the photoelectric cell. The spectral ab-

infarction and in pericarditis, the tracing can offer useful data. In some patients, in whom no heart disease can be demonstrated clinically and other laboratory tests were negative, the radiocardiogram may reveal an abnormal condition (Prinzmetal et al.).

INDICATOR-DILUTION METHODS

When a miscible substance is introduced into a unidirectional stream, it is diluted, dispersed, and transported away from the site of its introduction If the substance can be detected at a site downstream from the point of introduction, it will be identified at a lower concentration and for a greater period of time than that obtaining at its introduction (Fig. 4-88) Following its first arrival at the point of detection, the concentration of the indicator will increase for a time, then decline towards zero and finally disappear. The actual form of the curve of concentration with time between the instants of appearance and disappearance at the sampling site will be determined by the total volume of the system, the rate of flow through the system, the characteristics of the flow pattern, and the structural geometry of the system under consideration

In the application of the indicator-dilution principle to the study of the dynamics of the cardiovascular system, the factors of structural geometry of the vascular pathways and characteristics of flow, and their influences on dilution curves have not been precisely defined. In the vascular system, flow rate is a discontinuous function and the volume of the system may also be variable. Furthermore, in a system which permits recirculation of indicator before the initial quantity of indicator has been completely cleared, it is difficult to define the effect of recirculation with precision. In spite of these theoretical limitations, the indicator-dilution principle has a wide range of usefulness in the study of the circulation (Dow, 1956). Indeed, it is probable that more information concerning the status of the cardiovascular system can be obtained from a dilution curve than from any other single variable.

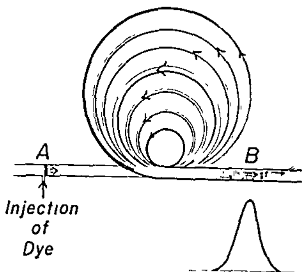


Fig. 4-88. Diagram illustrating the effect of paths of different traversal times such as would occur in the lungs on the distribution of a miscible substance introduced into a flowing stream at point A and observed at B. (*Courtesy of Dr. W. H. Helmholz, Jr.*)

Stewart (1897) first applied the indicator-dilution principle to the determination of *blood flow* while the studies of Hamilton et al (1932) established this method as a reliable technique A major factor was finding a satisfactory method of excluding from the calculations that portion of indicator which had reentered the central circulation through normal vascular pathways before all of the indicator had been cleared from the central circulation. The same workers (1921) applied the dilution principle to the calculation of *volumes* within the vascular system.

One of the major uses of indicator-dilution techniques from the diagnostic standpoint has been in association with cardiac catheterization. Information from indicator-dilution curves recorded after injection at selected sites in the heart can be combined with data derived from recordings of pressures and measurement by photometric and manometric techniques of the oxygen saturation of samples of blood withdrawn from selected sites in the heart and great vessels. The indicator-dilution technique has been applied extensively to the study of the abnormal cardiovascular system from a diagnostic standpoint Its use has reduced by at least 50 per cent incomplete or erroneous diagnoses in congenital heart disease studied with cardiac catheterization It has also become apparent that information of diagnostic value can be obtained from dilution curves in patients with valvular insufficiency. Other useful applications include determination of cardiac out-

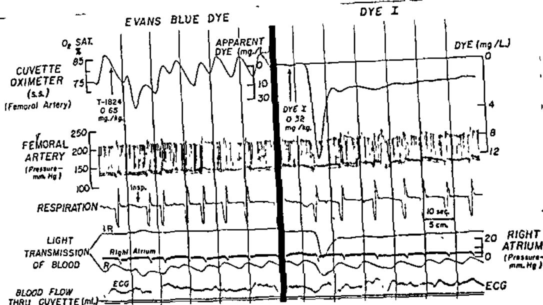


Fig 4-90. Demonstration of the interference of variations in oxygen saturation of arterial blood with recording of dilution curves of Evans blue dye by oximetry and the avoidance of such interference by use of a suitable indicator. The dilution curve on the left was recorded by the usual oximeter technique following injection of T-1824 into the pulmonary artery of a dog. The dilution curve on the right, recorded shortly after that shown on the left, was obtained with a modified oximeter circuit following the injection of indocyanine (dye I) (*Courtesy of Dr. I. J. Fox*)

ficult, if not impossible To circumvent this problem, a new dye, indocyanine green,[8] has been developed with maximum absorption in the region of 800 mμ and a detector photoelectric-cell—filter assembly with peak response in the same spectral region At 800 mμ the transmission of light by oxygenated and reduced hemoglobin is closely similar, and troublesome variations in oxygen saturation no longer distort the recorded dilution curve (Fig. 4-90). Indocyanine green has virtually replaced the blue dyes in many applications (authors, 1958)

RECORDED INDICATOR-DILUTION CURVES

Certain features of the dye-dilution curve recorded after a sudden single injection of indicator into the venous circulation in a healthy subject will be reviewed briefly The lower panel of Fig. 4-91 illustrates a dye-dilution curve which is within the range of normal values in every respect and was obtained in a patient 6 months after mitral commissurotomy At the time of the second study, this patient's cardiac output was within the range of normal values while at rest and pulmonary arterial pressure was not greatly above the normal range.

With a cardiac catheter in the pulmonary artery, a known amount of dye may be injected in 1 to 2 sec From the injection site (the point where dye and blood first start to mix), the dye is dispersed through the pulmonary vascular bed to the left atrium, and from there is pumped by the left ventricle into the systemic circulation Concentration of dye in the blood may be measured at any accessible location in the arterial system, less commonly in the left atrium itself, or in some other part of the venous vascular bed. The point at which the mixture of blood and dye is withdrawn for the determination of concentration of dye is referred to as *the sampling site.* A time interval elapses between the injection of dye and the first appearance of dye at the sampling site. This is called *the appearance time* (AT) and represents the fastest circulation time between injection and sampling sites It is the interval required for a minimally detectable concentration of dye to reach the sampling site by the fastest, most direct path. Greater amounts of dye continue to arrive at the sampling site and

[8] Indocyanine green is commercially available under the trade name Cardio-green, from Hynson, Westcott and Dunning, Inc, Baltimore, Maryland

sorption of oxygenated and reduced hemoglobin is different for the wavelength of 640 mμ, and Evans blue absorbs strongly at this wavelength. For detection of indicators such as Evans blue and for determination of the oxygen saturation of blood, an appropriate filter is placed in front of the photoelectric cell so that the peak response of the resulting photoelectric-cell-filter assembly is at approximately 640 mμ. The output from this assembly (the "red" cell) is fed to one side of a sensitive recording galvanometer while the output from a second photoelectric-cell-filter assembly with peak response at about 800 mμ (the "infrared" cell) is led to the other. The light transmitted by oxygenated and reduced hemoglobin is closely similar at 800 mμ so that a photoelectric-cell-filter assembly with peak sensitivity at these wavelengths responds principally to the total hemoglobin content of the blood while the absorption of Evans blue is practically zero at 800 mμ. The combined use of the two photoelectric-cell-filter assemblies greatly extends the range of usefulness of the oximeter in that its response is relatively independent of factors such as changes in pressure and rate of blood flow through the instrument, size of erythrocytes, and hemoglobin content of the blood.

Variations in the output of the photoelectric cells of the oximeter in response to changes in concentration of dye are recorded by direct-writing or photokymographic methods. The use of a direct-writing oscillograph or rapidly developed photographic paper makes the dilution curve immediately available for interpretation at the time of cardiac catheterization. Calibration techniques have been described in detail for the oximeter (Beard and Wood, Nicholson and Wood). The dynamic response characteristic of continuously recording oximeters or densitometers is of importance for faithful reproduction of rapid variations in indicator concentration which may be encountered in the circulatory system. The dynamic response of the cuvette oximeter and the factors which modify it have been described (Fox and coworkers). The continuous recording of dilution curves of the indicators just described, by means of the oximeter, suffers from a practical limitation in that changes in the oxygen saturation of the blood flowing through the detecting unit cause variations in its output. While these variations are small in the systemic arterial blood of normal persons and are eliminated when the subject breathes 100 per cent oxygen, the magnitude which they attain in venous blood precludes the accurate recording of dye curves for the venous circulation. Of more immediate importance to the present discussion, however, is the fact that patients with right-to-left shunts frequently exhibit variations in the oxygen saturation of arterial blood due to phasic changes in the magnitude of the shunt. At times the magnitude of these variations renders interpretation of dilution curves obtained from such patients dif-

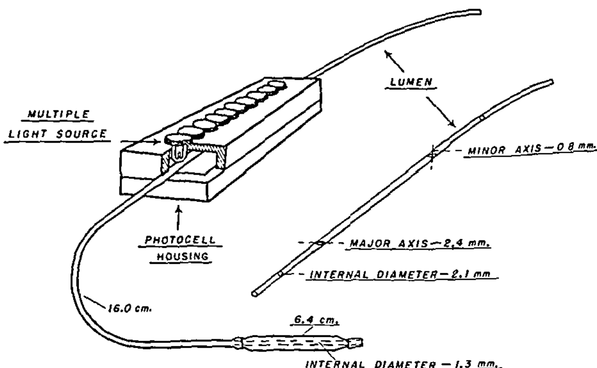


Fig. 4-89. Schematic diagram of cuvette oximeter.

In the description of dilution curves, normal and abnormal, there must be agreement on the definition of certain terms.

The *appearance time* (AT) is the interval from the instant of the beginning of injection of the indicator to its instant of first detection at the sampling site.

The *build-up time* (BT) is the interval from the instant of first detection of indicator at the sampling site to the instant of maximum concentration resulting from indicator which has traversed normal circulatory pathways.

The *recirculation time* (RT) is the interval from the instant of maximum concentration to the next definable peak of concentration of the indicator (if any), due principally to the indicator which has passed systemic capillaries.

The *disappearance time* (DT) is the interval from the instant of maximum concentration to the instant at which the declining concentration of indicator reaches a minimally detectable value eliminating the effect of recirculated indicator

The *passage time* (PT) is the sum of BT and DT.

The *peak concentration* (C_p) is the maximum concentration of indicator at the sampling site due only to that indicator which has traversed normal circulatory pathways.

The *average concentration* ($\bar{c}$) is the mean concentration of indicator at the sampling site during its first circulation, eliminating the estimated effect of recirculated indicator.

DETERMINATION OF CARDIAC OUTPUT AND CENTRAL BLOOD VOLUME

Apart from the measurement of circulation times as outlined, the quantitative values most commonly derived from indicator-dilution curves are cardiac output and central blood volume. Methods for the calculation of these values will be outlined briefly.

Instantaneous Injection Method. The *cardiac output* (Q) in liters/min is calculated according to the following equation.

$$Q = \frac{60I}{\bar{c}PT}$$

where I = quantity of indicator injected, in mg
$\bar{c}$ = average concentration, in mg/liter during the passage time (PT), in sec

The elimination of the effect of recirculated indicator is usually achieved by the method of Hamilton, in which the disappearance slope is considered to decline in an exponential fashion; the slope is determined by that portion of curve which has been inscribed shortly after the peak of concentration.

Several methods of measuring dilution curves have been introduced to simplify the determination of cardiac output. The formula of Hetzel is

$$Q = K\frac{60I}{0.5C_pBT}$$

where C_p = peak concentration, mg/liter
BT = build-up time, sec
K = 0.37 (constant) when indicator is injected into venous side of central circulation in human beings.

In this formula only two measurements (C_p and BT) are required; these can usually be made with a high degree of accuracy.

The terms *thoracic blood volume* and *central blood volume* refer to the volume of blood in which indicator has been diluted during passage from the site of injection to the sampling site. This volume includes not only the blood in the heart and lungs but also the volume contained in those portions of the vascular system limited by all points in the venous system from which indicator will pass to the central circulation in the same time interval as from the injection site, and by all points in the arterial system to which indicator will pass in the same time as to the sampling site The central blood volume, in milliliters, is given by the formula.

$$V = Q \times \bar{t}$$

where Q = flow in ml/sec
$\bar{t}$ = the mean transit time, in sec, i e, the average time required for the injected substance to pass from the injection to the sampling site

The physiological meaning and significance of values for central blood volume are at present uncertain, but a clearer interpretation may be possible by utilizing dilution curves obtained following injections and sampling at sites within the heart during the procedure of left heart catheterization.

Another calculation of central blood volume is that of Newmann et al., in which

the concentration rises to a maximum value. As the number of particles of dye being cleared from the central circulation and hence arriving at the sampling site diminishes, the curve recedes from the peak more slowly than the concentration increases. Toward the end of this disappearance portion of the curve, the indicator particles are joined by some of the fastest particles which have reentered the pulmonary circulation and are now traversing the systemic circulation for the second time. A second peak of concentration is reached when the maximum amount of recirculating dye passes the sampling site.

A dilution curve is a record of the change in the concentration of indicator with time. The dimensions of the curve are ordinarily affected by the volume rate of blood flow, the volume of blood between injection and sampling sites, the length and characteristics of the path which the dye must take, the speed and nature of the blood flow between injection and sampling sites, and a number of factors which have not been well defined. As the injection site is moved from a central to a more peripheral location, the time components (with the exception of the recirculation time) increase, and the concentration components decrease. In pathological or other states characterized by increased cardiac output, the time components are reduced and the concentration values are either reduced or unchanged. In patients whose cardiac output is low, all the time components are usually prolonged, and the peak of maximum concentration is not as well defined and not as great as in normal persons.

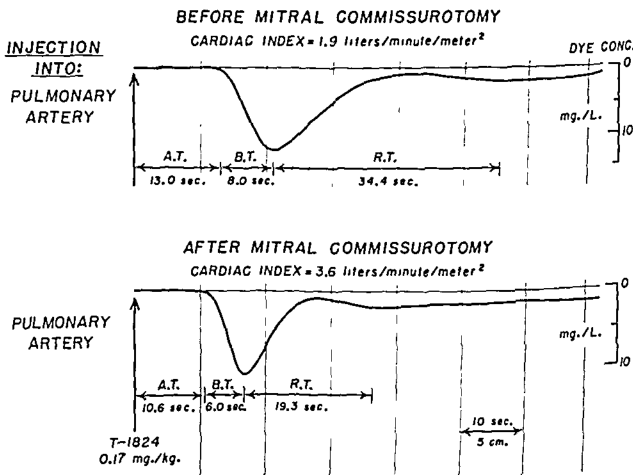


Fig. 4-91. Changes in dilution curves associated with congestive heart failure in a patient with mitral stenosis. The dilution curves in the upper and lower panels were recorded before and 6 months after a highly successful mitral commissurotomy.

corded at the time of cardiac catheterization before mitral commissurotomy; the lower curve was recorded 6 months after mitral commissurotomy. In the upper curve, the peak of maximum concentration is not sharp. The appearance, build-up, passage, and recirculation times are relatively long, and this is associated with the low cardiac output which was calculated to be 1.9 liters/min/m². Following operation, the time components are reduced to values within the normal range, and the peak of maximum concentration is now well defined. The cardiac index at this time was calculated to be 3 6 liters/min/m².

It has been demonstrated that dilution curves in patients with *valvular insufficiency* may [illegible]

[illegible] of combined right and left cardiac catheterization is shown in Fig. 4-92 Dilution curves were recorded from the left atrium and radial artery after injection of indicator into the left ventricle, left atrium, and pulmonary artery of a 40-year-old woman with severe mitral insufficiency without stenosis The marked prolongation of the disappearance phase is a notable feature of all curves In addition, when indicator was injected into the left ventricle, it appeared rapidly in the left atrium before it appeared in the radial artery This appearance was indicative of insufficiency of the mitral valve In this instance, the possibility of insufficiency of the aortic valve in addition to that of the mitral cannot be completely excluded. Identification of the insufficient valve is often possible by judicial selection of sampling and injection sites.

Congenital Heart Disease. The greatest value of the diagnostic application of indicator-dilution curves lies in their use in the *congenital heart diseases* characterized by intracardiac or great-vessel shunts. In such instances, the path taken by the indicator from injection to sampling site is in part or totally abnormal, and intelligent interpretation of the resulting dilution curves will permit the prediction of the anatomic nature of the defect in many instances Two types of curves, those characteristic of right-to-left and left-to-right shunts respectively (Fig 4-93), will be considered first, then the use of dilution curves in the more complicated congenital anomalies will be presented

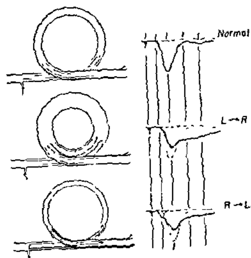


Fig. 4-93. Diagram representing dilution curves characteristic of left-to-right and right-to-left shunts and their major deviations from normal. (Courtesy of Dr H F. Helmholz, Jr.)

RIGHT-TO-LEFT SHUNTS. In patients suffering from cyanotic forms of congenital heart disease caused by the presence of a right-to-left shunt, the dilution curve recorded after injection of dye at a point upstream from the shunt has a characteristic contour. In Fig 4-94 are dilution curves recorded following injection into the main pulmonary artery and the right ventricle of a patient with ventricular septal defect through which both right-to-left and left-to-right shunts were occurring The differences in these curves are readily explained by the different pathways which the indicator traverses from the pulmonary artery or right ventricle as depicted in the diagrams above each dilution curve When dye is injected into the main pulmonary artery (Fig. 4-94A), it passes by way of normal vascular pathways to the left atrium and left ventricle and then to the arterial system. If a left-to-right shunt is present, the disappearance phase of the curve will be distorted according to the magnitude of the shunt. The appearance and build-up phases of the curve will be normal.

In contrast, the curve recorded after injection into the right ventricle (Fig. 4-94B) shows two characteristic features: (1) The appearance time is much shorter for this injection site than for that in the pulmonary artery; (2) there is an abnormal initial deflection due to dyed venous blood which is shunted across the ventricular septal defect in the right-to-

$$V = Q/S$$

where S = the slope of the declining limb of the curve

The negative sign of S is ignored and the estimated effects of systemically recirculated indicator are excluded. The proponents of this formula considered that the value obtained was a measure of the "lung blood volume" but the validity of this claim is uncertain.

Constant-rate Injection Method. The estimation of flow and volume can be made by indicator-dilution calculations from both constant-rate and instantaneous injection methods; these methods theoretically share essentially the same advantages and defects. When indicator is injected at a constant rate and the resulting "equilibrium" concentration in the circulation (C_e) can be determined, the cardiac output (Q) can be calculated in milliliters per second.

$$Q = I/C_e$$

where I = quantity, in mg/sec, of indicator injected

C_e = equilibrium concentration, in mg/liter

The determination of cardiac output can be achieved if a clear *plateau of concentration* can be defined on the inscribed dilution curve, or if a correction can be introduced for recirculated indicator. An accurate determination of cardiac output by this method is possible in the human subject, and the principle has been used by Grace et al. to measure blood flow in the descending thoracic aorta continuously for periods of about one minute.

Calculation of the value for the "central blood volume" can also be made by utilizing curves recorded after constant-rate injection.

INTERPRETATION OF DILUTION CURVES

Acquired Heart Disease. The changes seen in the contour of indicator-dilution curves in acquired heart disease, although often not dramatic, are frequently of diagnostic value. The changes are principally due to the presence of a reduced cardiac output in such patients (Fig. 4-91). The curves of Fig. 4-91 were obtained in a 41-year-old man suffering from mitral stenosis. The upper curve was re-

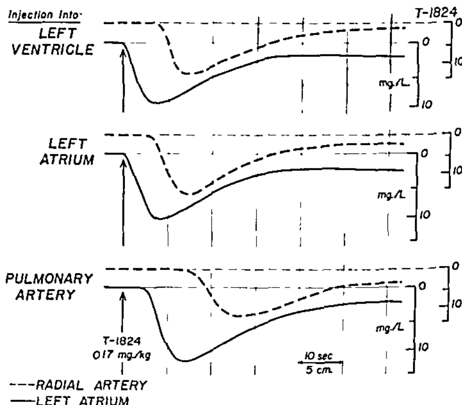


Fig. 4-92. Demonstration of *mitral insufficiency* by means of dilution curves. The dilution curve recorded from the radial artery is represented by the solid line, while the broken line is the dilution curve obtained with sampling from the left atrium

corded at the time of cardiac catheterization before mitral commissurotomy; the lower curve was recorded 6 months after mitral commissurotomy. In the upper curve, *the peak of maximum concentration is not sharp.* The *appearance, build-up, passage,* and *recirculation times* are relatively long, and this is associated with the low cardiac output which was calculated to be 1.9 liters/min/m². Following operation, the time components are reduced to values within the normal range, and the peak of maximum concentration *is now well defined. The cardiac index at this time was* calculated to be 3.6 liters/min/m².

It has been demonstrated that dilution curves in patients with *valvular insufficiency* may

[illegible]

of combined right and left cardiac catheterization is shown in Fig. 4-92. Dilution curves were recorded from the left atrium and radial artery after injection of indicator into the left ventricle, left atrium, and pulmonary artery of a 40-year-old woman with severe mitral insufficiency without stenosis. The marked prolongation *of the disappearance* phase is a notable feature of all curves. In addition, when indicator was injected into the left ventricle, it appeared rapidly in the left atrium before it appeared in the radial artery. This appearance was indicative of insufficiency of the mitral valve. *In this instance, the* possibility of insufficiency *of the aortic valve in addition* to that of the mitral cannot be *completely* excluded. Identification of the insufficient valve is often possible by judicial selection of sampling and injection sites.

Congenital Heart Disease. The greatest value of the *diagnostic* application of indicator-dilution curves lies *in their use in the congenital heart diseases* characterized by *intracardiac* or great-vessel shunts. In such instances, the path taken by the indicator from injection to sampling site is in part or totally abnormal, and intelligent *interpretation* of the resulting dilution curves will *permit* the prediction of the anatomic nature of the *defect in many* instances. Two types of curves, those characteristic of right-to-left and left-to-right shunts respectively (Fig. 4-93), will be consid[illegible]

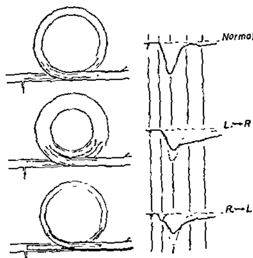


Fig. 4-93. Diagram representing dilution curves characteristic of left-to-right and right-to-left shunts and their major deviations from normal. (Courtesy of Dr. H. F. Helmholz, Jr.)

RIGHT-TO-LEFT SHUNTS. In patients suffering from cyanotic forms of congenital heart disease caused by the presence of a right-to-left shunt, the dilution curve recorded after injection of dye at a point upstream from the shunt has a characteristic contour. In Fig. 4-94 are dilution *curves recorded following injection into the main pulmonary artery* and the right ventricle of a patient with ventricular septal defect through which both right-to-left and left-to-right shunts were occurring. The differences in these curves are readily explained by the different pathways which the indicator traverses *from the pulmonary artery or right ventricle* as depicted in the diagrams *above each dilution* curve. When dye is injected into the *main* pulmonary artery (Fig. 4-94A), it passes by way of normal vascular pathways to the left atrium and left ventricle and then to the arterial system. If a left-to-right shunt is present, the disappearance phase *of the* curve will be distorted according to the *magnitude of the shunt.* The appearance and build-up phases *of the curve* will be normal.

In contrast, the curve recorded after injection into the right ventricle (Fig. 4-94B) shows *two* characteristic features. (1) The *appearance time is much shorter for* this injection site than for that *in the pulmonary* artery, (2) there is an abnormal initial *deflection due* to dyed venous blood which is shunted *across* the ventricular septal defect in the right-to-

$$V = Q/S$$

where S = the slope of the declining limb of the curve

The negative sign of S is ignored and the estimated effects of systemically recirculated indicator are excluded. The proponents of this formula considered that the value obtained was a measure of the "lung blood volume" but the validity of this claim is uncertain.

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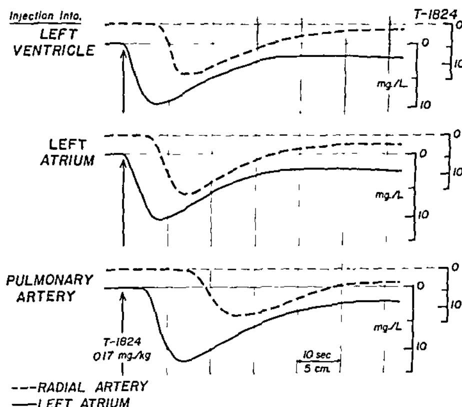


Fig. 4-92. Demonstration of *mitral insufficiency* by means of dilution curves. The dilution curve recorded from the radial artery is represented by the solid line, while the broken line is the dilution curve obtained with sampling from the left atrium.

greater magnitude for blood from the inferior vena cava (Fig. 4-95), or it may be absent for blood from the latter site. This preferential flow of inferior caval blood across the defect is due to the relation of the fossa ovalis to the inferior vena cava and has its counterpart in the fetal circulation. When a right-to-left shunt, which is greater from the superior vena cava than from the inferior vena cava, has been detected, it is likely that the interatrial communication *is not in the usual location* In the authors' experience, this occurs almost exclusively in cases in which the interatrial septal defect is located above the region of the fossa ovalis and is associated with an anomalous connection of the right superior pulmonary vein. The differentiation of this condition from atrial septal defect of the usual type has considerable importance from the standpoint of surgical correction

LEFT-TO-RIGHT SHUNTS. Contours of dilution curves recorded after injection of dye at points upstream from the pulmonary artery in patients having shunts only in the left-to-right direction are similar, irrespective of the location of the intracardiac or great-vessel shunt In such curves, the appearance and build-up times fall within the normal range but the peak of maximum concentration is reduced (Figs 4-93 and 4-96). The disappearance phase of the dilution curve is, however, grossly abnormal in that the decline in concentration after the peak is markedly slowed. Usually no secondary peak of concentration due to systemic recirculation of indicator is identifiable. The degree of abnormality, that is, the reduction in the peak of concentration and the slope of the disappearance phase, is roughly related to the magnitude of the left-to-right shunt The explanation of the contour characteristic of this type of *hemodynamic anomaly occurring* through a ventricular septal defect is evident from Fig. 4-96. When indicator is injected into the main pulmonary artery or at points upstream from this vessel, it circulates through the lungs, returning to the left atrium and left ventricle, whence a fraction determined by the magnitude of the left-to-right shunt reenters the pulmonary artery, and the remaining dye passes to the sampling site in a normal manner. Because of the large pulmonary blood flow due to the left-to-right shunt, the concentration of dye entering the aorta on first circulation is smaller than would be expected, and the peak concentration at the sampling site is therefore reduced The recirculation of the most rapidly traveling particles of dye through the pulmonary vessels and back to the left ventricle allows for a further entry of dye into the aorta before the disappearance phase of

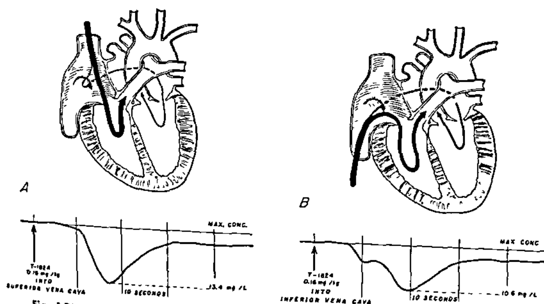


Fig. 4-95. A and B. Preferential right-to-left shunting from the inferior vena cava via an atrial septal defect located in the region of the fossa ovalis.

left direction. Since this dye enters the aorta immediately following injection into the right ventricle, it arrives at the radial artery sampling site much sooner than the second peak due to the dye which has traversed the normal pathway through the lungs. The dilution curve is reduced in amplitude in comparison to that following injection into the pulmonary artery. Occasionally, when a large right-to-left shunt is present, and a preferential injection of dye is made in the right ventricle toward the aortic orifice, the initial deflection of the right-to-left shunt may be of great magnitude.

It is clear how the site of the defect through which a right-to-left shunt is occurring may be localized by this method. If the indicator is injected upstream from the site of the right-to-left shunt, the dilution curve shows the characteristic abnormalities just described. If the indicator is injected downstream from the site of the right-to-left shunt, these features will not be evident. In this way, it is possible to localize a right-to-left shunt through a patent ductus arteriosus, a ventricular septal defect, or an atrial septal defect. In patent ductus arteriosus with pulmonary hypertension, dilution curves recorded at the femoral and radial arteries give evidence that the proportion of shunted blood reaching the femoral artery is greater than that reaching the radial artery (Burchell et al., 1953). A useful method whereby the right-to-left shunt taking place across a defect can be quantitated from the two components of the abnormal dilution curve has been described in a previous article (Swan et al., 1953).

Certain features of the direction and magnitude of right-to-left shunts in atrial septal defects may be of differential diagnostic significance. In patients with *atrial septal defects* of the usual type, located in the region of the fossa ovalis, small right-to-left shunts frequently occur. Usually the magnitude of these shunts is small, so that abnormal desaturation of peripheral arterial blood is not seen. Figure 4-95 depicts the circulation in an instance in which a small right-to-left shunt occurred at the atrial level The recorded dilution curves seen below the diagram are characterized by appearance times which are *shorter* than for dilution curves obtained following injection into the right ventricle, and by a separate peak of concentration (Fig. 4-95B) and an early break (Fig 4-95A), indicating the presence of a right-to-left shunt. When this occurs, it is of

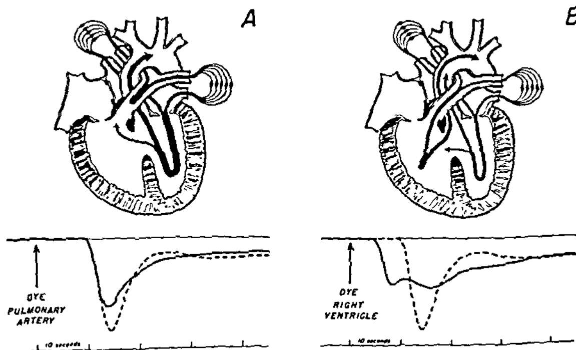


Fig. 4-94. Diagram of the method of localizing the site of a right-to-left shunt from indicator-dilution curves There is a large ventricular septal defect, through which a considerable right-to-left shunt and a small left-to-right shunt are occurring, with severe pulmonary hypertension. A. Dye is injected into the main pulmonary artery B. Dye is injected into the right ventricle. The broken line indicates the anticipated dilution curve in a normal circulation.

greater magnitude for blood from the inferior vena cava (Fig 4-95), or it may be absent for blood from the latter site. This preferential flow of inferior caval blood across the defect is due to the relation of the fossa ovalis to the inferior vena cava and has its counterpart in the fetal circulation. When a right-to-left shunt, which is greater from the superior vena cava than from the inferior vena cava, has been detected, it is likely that the interatrial communication is not in the usual location. In the authors' experience, this occurs almost exclusively in cases in which the interatrial septal defect is located above the region of the fossa ovalis and is associated with an anomalous connection of the right superior pulmonary vein. The differentiation of this condition from atrial septal defect of the usual type has considerable importance from the standpoint of surgical correction.

LEFT-TO-RIGHT SHUNTS. Contours of dilution curves recorded after injection of dye at points upstream from the pulmonary artery in patients having shunts only in the left-to-right direction are similar, irrespective of the location of the intracardiac or great-vessel shunt. In such curves, the appearance and build-up times fall within the normal range but the peak of maximum concentration is reduced (Figs 4-93 and 4-96). The disappearance phase of the dilution curve is, however, grossly abnormal in that the decline in concentration after the peak is markedly slowed. Usually no secondary peak of concentration due to systemic recirculation of indicator is identifiable. The degree of abnormality, that is, the reduction in the peak of concentration and the slope of the disappearance phase, is roughly related to the magnitude of the left-to-right shunt. The explanation of the contour characteristic of this type of hemodynamic anomaly occurring through a ventricular septal defect is evident from Fig 4-96. When indicator is injected into the main pulmonary artery or at points upstream from this vessel, it circulates through the lungs, returning to the left atrium and left ventricle, whence a fraction determined by the magnitude of the left-to-right shunt reenters the pulmonary artery, and the remaining dye passes to the sampling site in a normal manner. Because of the large pulmonary blood flow due to the left-to-right shunt, the concentration of dye entering the aorta on first circulation is smaller than would be expected, and the peak concentration at the sampling site is therefore reduced. The recirculation of the most rapidly traveling particles of dye through the pulmonary vessels and back to the left ventricle allows for a further entry of dye into the aorta before the disappearance phase of

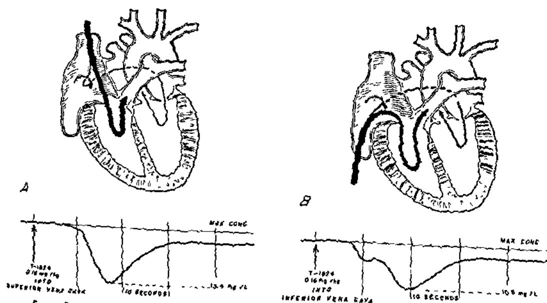


Fig. 4-95. A and B Preferential right-to-left shunting from the inferior vena cava via an atrial septal defect located in the region of the fossa ovalis.

that dye which originally entered the aorta has progressed to any great extent. As the dye becomes more uniformly mixed with the blood in the left atrium, left ventricle, and pulmonary vessels, this system may be regarded as a central pool from which a proportion of dye is cleared in each circulation, and the prolonged disappearance phase of the dilution curve reflects the slow release of dye from this pool.

In certain conditions characterized by left-to-right shunting of blood, indicator-dilution curves may play a considerable role in determining an exact diagnosis. These conditions are principally those characterized by drainage of blood from the pulmonary vein to the right atrium or to one of its tributary veins. *Partial anomalous pulmonary venous drainage* due to an anomalous connection of all the veins of one lung to the right atrium or tributary thereof with closed atrial septum is a useful example of the definition of abnormal vascular pathways by means of indicator-dilution curves (Fig. 4-97). The dilution curves recorded after injection of indicator into the right and left pulmonary arteries are shown beneath the respective diagrams which depict the pathway taken by indicator injected at each of these sites. Because the vascular pathway from the left pulmonary artery to the systemic arterial sampling site is normal and complete (Fig. 4-97B), the indicator-dilution curve recorded after injection into the *left* pulmonary artery is normal. However, the gross abnormality of the vascular pathway from the right lung to the systemic arterial system, which now includes the right side of the heart (Fig. 4-97A), is responsible for the typical dilution curve obtained in this condition when the indicator is injected into the *right* pulmonary artery. The appearance of dye at the systemic arterial system is greatly delayed. The peak deflection is reduced considerably, and there is a prolonged slope of declining concentration.

Patients with atrial septal defects not uncommonly have an associated partial anomalous pulmonary venous connection. In such an instance, the dilution curves will show features similar to those seen in Fig. 4-97, but in addition the disappearance phase of the curve will be distorted to a minor degree after injection of the indicator into the pulmonary artery supplying the normally connected lung.

The principal hemodynamic anomaly seen in the usual case of atrial septal defect with normally connected pulmonary veins is a left-to-right shunt of such magnitude that the pulmonary blood flow is two or more times the systemic flow. Indicator-dilution curves ob-

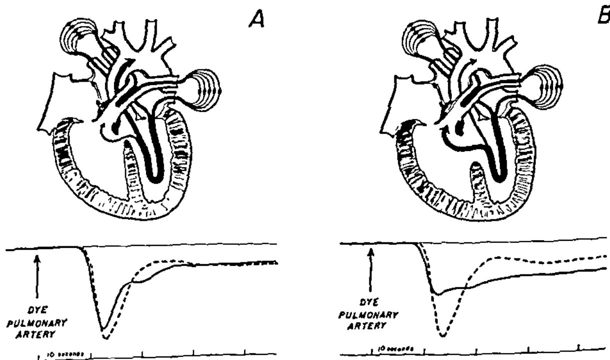


Fig. 4-96. Changes in dilution curves in the presence of a left-to-right shunt. The examples illustrate the effect of a small defect (A) and a large defect (B) which no longer impede the flow of blood in the left-to-right direction.

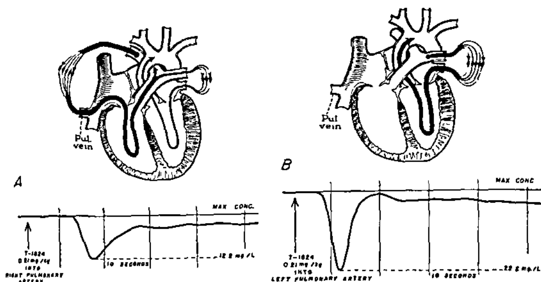


Fig. 4-97. Demonstration by indicator-dilution curves of an anomalous connection of the right pulmonary veins to the inferior vena cava in a patient with an intact atrial septum Below each schematic diagram of the pathway taken by indicator, after injection into (A) the right or (B) the left pulmonary artery, is a dilution curve recorded from a patient with such an anomaly.

tained in a typical example of this condition following injection of dye into the left and right pulmonary arteries (Fig. 4-98) may be readily interpreted on the same basis as those in Fig 4-97. They are taken to indicate that, of the blood traversing the right lung (Fig 4-98A), the greater part drains anomalously to the right atrium and right ventricle, while a greater proportion of blood traversing the left lung (Fig. 4-98B) drains normally to the left ventricle. This difference in the proportion of blood draining anomalously from each lung is due to the proximity of the left atrial orifices of the *right* pulmonary veins to an atrial septal defect located in the region of the fossa ovalis, in contrast to the anatomic relation of the orifices of the *left* pulmonary veins to such a defect. It is a usual finding that a greater proportion of the blood traversing the right lower lobe is shunted in the left-to-right direction than of that traversing the right upper lobe

The absence of preferential left-to-right shunting of blood from the right lung is un-

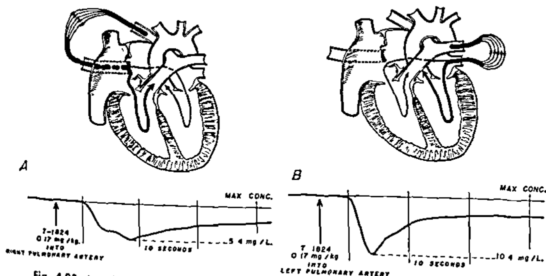


Fig 4-98. A and B The central circulation *in the usual* case of atrial septal defect as demonstrated by indicator-dilution curves.

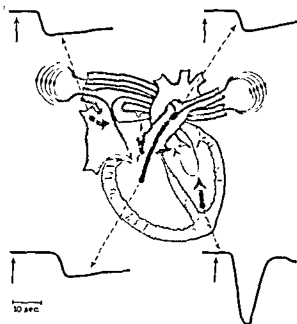


Fig. 4-99. The central circulation and the method of demonstrating total anomalous pulmonary venous drainage by means of indicator-dilution curves. In this diagram an anomalous connection of the pulmonary veins to the posterior portion of the right atrium is assumed

usual in cases of atrial septal defect. If such preferential shunting is not demonstrated by indicator-dilution curves and if the possibility of preferential injection into the pulmonary artery of the right upper lobe instead of into the right main pulmonary artery can be excluded, this is of diagnostic significance. Dilution curves of similar contour are consistently obtained after injection into each main pulmonary artery in cases of ventricular septal defect or of common atrioventricular canal.

Dilution Curves in Complex Congenital Heart Disease. COMPLETELY ANOMALOUS PULMONARY VENOUS DRAINAGE. This hemodynamic anomaly occurs in the conditions of common atrium and anomalous connection of all pulmonary veins to the right atrium, superior or inferior venae cavae, or their tributaries (Fig. 4-99). The essential abnormality is a mixing of systemic and pulmonary venous blood in the right atrium with egress to the left atrium and left ventricle occurring only through an interatrial communication. In certain cases, however, interatrial mixing of bloods is incomplete and there remains a preferential shunt of inferior caval blood to the left atrium so that, if the anomalous connection is to the superior vena cava or one of its tributaries, the oxygen saturation of systemic arterial blood is less than the saturation of pulmonary arterial blood; conversely, if the anomalous pulmonary veins drain into the inferior vena cava, the opposite situation obtains. The dilution curves obtained by injection of indicator at any site on the right side of the heart are similar in contour but, in contrast to the usual situation, the appearance time is shorter when the dye is injected into the right atrium or venae cavae than when it is injected into the right ventricle or pulmonary artery. These dilution curves characterizing a large left-to-right shunt show major differences in contour between those recorded after injection of the dye into the right ventricle or pulmonary artery and those recorded after its injection into the left atrium or ventricle. The presence of preferential right-to-left shunting of inferior caval blood, which may cause differences between the oxygen saturation of systemic and pulmonary arterial blood, may be demonstrated by comparison of dilution curves recorded after inferior and superior caval injections.

DRAINAGE OF BLOOD FROM AN INDIVIDUAL PULMONARY VEIN. At cardiac catheterization, the catheter tip may enter a pulmonary vein and pass into the lung field, this occurs more frequently on the right than on the left side. By comparison of dilution curves obtained after an injection of dye into the pulmonary vein and other locations, such as the left ventricle or venae cavae, the drainage of the pulmonary vein may be defined in terms of the other sites. The most important comparison concerns the right pulmonary veins with the inferior and superior venae cavae. If identical dilution curves are obtained after injections of dye at these positions or if the curve from the pulmonary vein is intermediate in contour between the caval curves (when these differ), then the drainage of blood from the pulmonary vein in question is similar to that of caval blood and it is likely that such a vein is anomalously connected. When the dilution curves differ, and there is a deflection which is of greater magnitude and occurs sooner after the indicator is injected into the pulmonary vein than after it is injected into one of the venae cavae, this deflection indicates that blood from the pulmonary vein is draining in a manner different from the caval blood, and it is likely that such a vein is connected normally to the left atrium.

THE PRESENCE OF A FUNCTIONAL PATH TO THE PULMONARY ARTERY OTHER THAN VIA THE AORTA. In certain conditions, such as common truncus arteriosus, atresia of the pulmonary valve, and certain varieties of atresia of the tricuspid valve, all the blood entering the pulmonary vessels has passed through the aortic valve. The demonstration of this hemodynamic abnormality may be of great practical importance in determining the possibility of surgical correction of the complex malformations. If a dilution curve obtained after injection of indicator into the inflow portion of the right ventricle is identical to a curve obtained after injection into the aorta just above its valve, then no direct path of functional significance exists from the right ventricle to the pulmonary artery. If such curves differ due to the presence of a functioning pathway between the right ventricle and the pulmonary artery, then the dilution curve obtained after injection of indicator into the inflow part of the right ventricle will show a reduced initial deflection and a different disappearance phase (perhaps characterized by an identifiable peak of concentration) in comparison to the curve following injection of indicator above the aortic valve. The difficult differentiation of pulmonary atresia from tetralogy of Fallot in its more classical form may be achieved by this technique. The same principle may be used to identify the absence of a functioning pathway from the right atrium to the pulmonary artery in patients suspected of having tricuspid atresia (Swan and Wood, 1953). Identity of contour again indicates that a common pathway exists for all the indicator whereas, if an independent flow can occur by way of the tricuspid valve to the pulmonary artery, then the dilution curves differ, as outlined above.

IDENTIFICATION OF A CENTRAL GREAT VESSEL IN WHICH THE INTRAVASCULAR PRESSURE AND THE OXYGEN SATURATION DO NOT DIFFER SIGNIFICANTLY FROM THOSE OF SYSTEMIC ARTERIES. A central great vessel with these characteristics may be either the pulmonary artery or aorta. Frequently, the position of the valve guarding such a vessel may not allow certain identification at cardiac catheterization because

... dye into the vessel will show a short appearance time and an initial deflection of considerable magnitude, whereas, should it be the pulmonary artery, the initial deflection would be of small magnitude and the appearance of dye much less rapid. This technique has been found of considerable practical value.

CONCLUSIONS

Experience gained in a wide application of the indicator-dilution principle during diagnostic cardiac catheterization allows for a critical appraisal of this technique in its diagnostic application. It has been found to be invaluable for localization and quantitation of right-to-left shunts, and further elucidation of the nature of left-to-right shunts. In atrial septal defect, for example, this technique has increased the understanding of the hemodynamics associated with the disorder. In certain complex anomalies of the heart and great vessels, information has been obtained which could not be collected in any other way. One of the major values of indicator-dilution techniques is as an integral part of cardiac catheterization. Their application to diagnosis is greatly facilitated by the use of rapidly developing photographic paper, which makes the information from each dilution curve available immediately to the physician performing the catheterization and allows him to alter the procedure so that the most accurate and complete diagnosis can be obtained.

The successful diagnostic application depends on whether or not the concentration curves recorded resolve accurately the separate peaks of indicator concentration due to the fact that the dye traverses pathways of different lengths. In adults, the interval of time between the peaks of concentration due to that dye passing directly to the systemic circulation and that traversing the lungs is of sufficient duration to allow the separate peaks of concentration to be resolved with accuracy. On the other hand, in infants and young children, the rate of passage of dye through the lungs may be so rapid that poor resolution of the peaks of concentration is recorded by the detecting instrument. This is more likely to occur in dilution curves recorded by means of the ear-piece oximeter than with the whole-blood cuvette oximeter. However, poor resolution is only in part an instrumental problem,

since the individual components of a dilution curve may be smeared out during the passage of the blood-dye mixture to the peripheral circulation in those patients in whom the central circulation is extremely rapid and the peaks of concentration occur in rapid succession.

The position of the tip of the catheter at the time of injection of the indicator is extremely important, for the dilution curve recorded depends on the location of the site of injection. When dye is injected at certain locations, such as the pulmonary arteries, the position of the catheter tip should be confirmed roentgenographically during the injection since it can change position spontaneously owing to the motion of the diaphragm or the beating of the heart. Furthermore, it is frequently possible in spite of correct positioning of the catheter for dye to pass preferentially into one or another location such as the aorta through a ventricular septal defect or into one or another lobar artery of the right lung from the right main pulmonary artery. In the diagnostic application of dilution curves, therefore, one must always be on guard against mistaken interpretation due to such circumstances.

7

Visualization of the cardiovascular and the peripheral vascular system

Angiocardiography
AUGUSTÍN CASTELLANOS

Thoracic Aortography
AUGUSTÍN CASTELLANOS

Peripheral Arteriography, Aortography, and Venography
R. B. LYNN

ANGIOCARDIOGRAPHY

HISTORY

After the preliminary trials of Moniz, Lopo de Carvalho, and Lima and others, Castellanos, Pereiras, and Garcia (1937) devised a safe, rapid, and easy technique for the contrast visualization of the right chambers of the heart and of the pulmonary artery with its branches, in order to make the anatomical diagnosis of congenital heart disease *in children.* They called their method *angiocardiography* They studied the normal image of the right chambers and the pulmonary artery in the frontal and lateral views, as well as the images of the most frequently found malformations, such as interventricular defect, pulmonary stenosis, and tetralogy of Fallot.

A year later, Robb and Steinberg applied the same technique *to adults.* They observed that the radiopaque solution, after passing through the capillary bed of the lungs, allowed the visualization of the left heart chambers, the aorta, and the branches of the aortic arch.

Castellanos and coworkers introduced the term angiocardiography and described the *dextroangiocardiogram.* Robb and Steinberg described the *levoangiocardiogram* in adults.

Castellanos, Pereiras, and Garcia (1937) introduced the term angiocardiography in order to designate the radiographic visualization of the cardiac chambers and the great vessels using, as a contrast medium, a radiopaque solution. They later (1938) described *superior and inferior cavography* (a modification of intravenous angiography), in order to study the superior and inferior venae cavae and the venous trunks from which they originate.

Chavez, Dornbecker, and Celis (1947) injected a radiopaque solution into the right ventricle through a Nelaton tube. They called this method *direct angiocardiography.* Jonsson, Broden, and Kernell (1949) used a Cournand catheter for the same purpose and were able to visualize any of the cardiac chambers or vessels. In this method, the injection is done with the aid of a special gadget. They call this method *selective angiocardiography.*

Beato and Ponsdomenech (1950) introduced a trocar through the thoracic wall of human beings into the cardiac chambers, and injected a contrast solution with the aid of a dos Santos apparatus They called their method *cardioangiography*

Oppenheimer et al (1956) described a new method, also called cardioangiography, based on the injection of CO_2 into the ventricular cavities. The method is safe and is useful in selected cases

TECHNIQUE

Position of the Patient. Each cardiac malformation gives a more or less typical image in the

frontal, lateral, oblique, anterior, right, or left positions. Depending on the anatomical characteristics of the cardiac cavities and great vessels and on the hemodynamics of the heart, an image or a sign would become evident in certain positions and not in others. For this reason, when employing a *single-film changer*, the choice of an appropriate radiological position is of utmost importance. *Biplanes*, which allow the taking of two simultaneous views at 90° angles, simplify the diagnostic procedure and, at the same time, increase the percentage of accuracy *Single-film* changers, besides being more cumbersome, require individual injections for each position.

By using *double-film changers*, both frontal and lateral positions can be taken, as well as both obliques and both right and left anterior positions The oblique positions are always used by Swedish investigators

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The most commonly used are: (1) *Diodrast*, manufactured by Winthrop-Stearns, *Perabrodil*, by Merck, and *Umbradil*, by Astra (chemically identical, the diethanolamine salt of 3,5-diiodo-4-pyridone-N-acetic acid). (2) *Urokon sodium*, produced by Mallinckrodt, is chemically different from the above media. It is the sodium salt of 3-acetylamino-2,4,6-triiodobenzoic acid It comprises 65 per cent iodine and is used in a 70 per cent concentration.

In patients with no serious cardiac failure, *a 70 per cent concentration* is about right In patients with severe hypoxia or polycythemia and severe dyspnea, good results can be obtained by the injection of *50 per cent solutions* through the jugular veins For intravenous angiocardiography, 1 to 1 5 ml/kg is the optimum dose. Large hearts sometimes require up to 1.75 ml/kg of body weight

Duration of the Injection. In order to obtain good, thoroughly contrasted images, the injection must be completed in less than one second

Instruments and Equipment. For newborn and very young infants, the 18-, 16-, or 14-gage Becton and Dickinson trocars should be used. For older children and adults, there are specially made cannulas. The Robb and Steinberg trocar is also widely used. It is a 12-gage cannula manufactured by Becton and Dickinson, and consists of three pieces and a two-way passkey for syringe connection. It must be used with concentric tipped syringes.

Since 1948, the Becton and Dickinson Company has also been manufacturing two special models. One is a long, 12-gage, four-piece trocar without passkey. The other is a 10-gage, four-piece simple trocar. Later on, the company introduced a new type consisting of two pieces and a stylet

For the injection of volumes up to 10 ml, the standard, metal-tipped B-D syringes are adequate. For the injection of volumes greater than 10 ml (12- or 10-gage trocars), a special metal-tipped syringe must be used with the lumen of the tip greater than in the standard syringe. The syringes are manufactured for capacities of 20, 30, and 50 ml. As a general rule, the internal diameter of the tip must be equal to, or slightly larger than the internal diameter of the trocar.

Most recently, the use of a Cournand catheter has become widespread. This catheter has a very small lumen, and its length of 120 cm makes it very practical. However, a special *pressure apparatus* must be employed in order to obtain good results. The technique is a modification of the method introduced by Chavez, Dornbecker, and Celis. Using a No. 12 or No. 14 Nelaton sound introduced through the external jugular vein, it is possible to inject a radiopaque solution into the cardiac cavities. The injection is given with a special B-D syringe.

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1 *Durand's*, manufactured by Drapier, Inc. It has the disadvantage of its low pressure, never above 3.5 kg/cm².

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SERIOGRAPHS OR ANGIOGRAPHS Many ultrarapid plate changers for angiocardiography have been introduced. Only the most important will be mentioned.

1. *The Sanchez Perez automatic seriograph*, a biplane apparatus having a 10-in. chassis. It has a maximum speed of 2 plates/sec.

2. *The Fairchild camera*, widely used. Each magazine has a 9½ by 9½-in. roll, 75 ft long. Two intensifying screens hold the film firmly at the

time of exposure. Once the impression is made, the screens are separated, the film is moved forward, and a section of unexposed film occupies its place between the two screens This sequence is repeated automatically several times. There is a fixed grid for each magazine. The magazine can be used in either the vertical or horizontal position. The *Syncro-trol*, a gadget for the control of the speed of exposure, makes the Fairchild camera quite useful

The film is developed and fixed in a cylindrical tank of stainless steel It has a waterproof electric motor, and the developing, fixing, and washing of the exposed film are done automatically.

3 Elema (Stockholm, Sweden), a biplane apparatus Each plane has a tube set in a special

posi-

placed

12-in

roll of film Its speed varies from 1 plate every 10 sec to 12 plates/sec.

O... of the advantages of the Elema is its so-

matic 1,000 C E, a monophasic apparatus having four rectifying tubes with a maximum output of 1,000 ma and 120 kv, and the Triplex Automatic 1,000 C E, a triphasic apparatus with six rectifying tubes and a maximum output of 1,000 ma and 125 kv Through an electronic contact, the switching capacity is 25 exposures/min

4 *Schonander* (Stockholm, Sweden) consists of a separate unit which makes possible its combination with another similar unit to make a biplane Both plate changers and tubes are easily transported, and can be placed in either vertical or horizontal positions, depending on each particular case.

The main difference between the Elema and the Schonander lies in the film Whereas the Elema uses a roll of film, the Schonander uses single plates, their sizes being 10 by 12 in. or 14 by 14 in

Two generators can be used, one for each tube, or one generator can be used for both tubes In the latter case, the 1,000-ma unit with 100 kv maximum is necessary, the same ma and kv factors, as well as the same exposure factors must be used for both plate changers When using two generators, different factors can be used for each plate changer

The magazine has a capacity of 30 plates An exposure selector can be used for the control of the speed of exposure If the selector is not used, the apparatus automatically takes plates at the rate of 2, 4, or 6/sec Its maximum capacity is, therefore, 6 plates/sec

A special gadget permits the registration of the cardiac cycle at which the film is exposed, as well as the time taken for the injection of the radiopaque solution.

Ordinary methods are used for developing, fixing, and washing the films.

Fatal Accidents. The rate of fatal accidents varies with the statistics of the various investigators. Dotter and Jackson (1950) compiled a list of fatal accidents during the performance of angiocardiography. They state that in the United States of America, Canada, England, and Sweden, a grand total of 6,824 angiocardiographies was performed in 182 hospitals, with 26 deaths, i.e., a mortality of 0 37 per cent, or one death per 200 injections.

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This committee proposed a series of recommendations which were sent to the members of the society and were found very helpful.

In 1950, the Scientific Council of the American Heart Association established a committee to evaluate the risks of catheterization of the cardiac chambers and angiocardiography This committee arrived at important conclusions which were published in several scientific journals Generally speaking, the mortality rate in angiocardiography depends on many factors, the most important of which are the following: (1) dosage employed; (2) chemical nature of the radiopaque substance used, (3) clinical or physiopathological condition of the patient, (4) selection of the patient; (5) experience of the performing team

Radiation Received by the Patient. The great number of radiographs obtained at present during the performance of angiocardiography with the aid of biplane, ultrarapid apparatus, has suggested the necessity of studying the amount of radiation received by the patient Considering that a biplane works at a rate of 6 plates/sec, and functions during a period of 5 sec, this would mean an average of 60 exposures during each exploration With each exposure, 1 1 r are absorbed, making a total of 66 r as an average, when employing a distance of 30 in from focus to plate and 500 ma and 77 kv, and 0 1 sec for each exposure. The radiation received by the patient during telecardiography, esophagograms, catheterizations, etc., should also be taken into consideration

THE DEXTROANGIOCARDIOGRAM

The dextroangiocardiogram gives information about the following anatomical elements (Fig. 4-100)

1. *The great veins* opening into the heart:

frontal, lateral, oblique, anterior, right, or left positions. Depending on the anatomical characteristics of the cardiac cavities and great vessels and on the hemodynamics of the heart, an image or a sign would become evident in certain positions and not in others For this reason, when employing a *single-film changer*, the choice of an appropriate radiological position is of utmost importance. *Biplanes*, which allow the taking of two simultaneous views at 90° angles, simplify the diagnostic procedure and, at the same time, increase the percentage of accuracy. *Single-film changers*, besides being more cumbersome, require individual injections for each position.

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DIAGNOSIS OF CERTAIN CARDIOVASCULAR MALFORMATIONS

Anomalies of the Superior Vena Cava. Thanks to angiocardiography, the diagnosis of anomalies of the superior vena cava is possible. Castellanos and coworkers demonstrated that intravital diagnosis of these malformations is possible by means of dextroangiocardiograms Castellanos and Rodriguez Diaz (1948) described the various types of anatomical malformations which may be found while dealing with the surgical correction of congenital cardiopathies. The most frequently found pattern is the persistence of the left superior vena cava, with or without innominate veins This vessel goes, in some cases, to the right atrium, but in other cases is connected to the left

Absence of the Inferior Vena Cava. When a dye is injected through one of the saphenous veins, a typical image is observed. All the blood from the abdomen and lower extremities reaches the heart *via the left azygos vein,* which generally empties into a left superior vena cava.

Congenital Absence of One of the Pulmonary Arteries. In a dextroangiocardiogram, and in frontal projection only, only one of the two pulmonary arteries is visible. The other artery cannot be seen because it does not exist

Right-sided Pulmonary Artery Trunk. In these cases, the pulmonary artery trunk is superiorly located, at the right border of the cardiac silhouette. Generally, a left branch arises from it, just to the right of the midline, and presses on the trachea, the esophagus, or both.

Isolated Pulmonary Stenosis. In the *valvular* type, the "filling" defect is plainly seen on anteroposterior or lateral plates; just above it, the characteristic dilatation of the artery is also evident (Fig. 4-101)

If there is an *infundibular stenosis,* the defect is found at the lowest part of the infundibulum, i e , at its entrance to the right ventricle, and the dilatation is found at the infundibulum itself, just below the pulmonary sigmoids The dilatation is seen, then, near the center of the cardiac shadow, and does not become part of the medial arch of the cardiac outline

The *stenosis of one of the branches of the pulmonary artery,* as well as the multiple narrowings occasionally seen in various peripheral branches, can be visualized clearly in the radiographic plates, especially in the frontal projection

Idiopathic Dilatation of the Pulmonary Artery. This is seen best on lateral plates. The great dilatation of the pulmonary artery is evident, but there is no "filling" defect at the pulmonary valve region

Trilogy of Fallot. In the frontal, as well as in the LAO, position, the pulmonary stenosis is clearly outlined and the left-to-right arterial shunt is also well defined. In most cases, there is a valvular stenosis and a poststenotic dilatation of the trunk of the pulmonary artery.

Tetralogy of Fallot. The diagnosis of this anomaly is simplified by the dextroangiocardiogram in a frontal or LAO projection (Fig. 4-102) *Simultaneous filling of the aorta and pulmonary artery and its branches* is typical *The aorta is wide in most cases,* and *the pulmonary artery trunk and its branches are hypoplastic in the majority of cases* There is an anatomical type in which *valvular stenosis with poststenotic dilatation of the pulmonary artery trunk and one or both branches,* are found. In such cases, an erroneous diagnosis of Eisenmenger's complex can be easily made.

Patent Ductus Arteriosus. In cases *without* pulmonary hypertension, a *filling defect* may be observed in the trunk of the pulmonary artery, especially during diastole. This is due to a jet of blood coming from the aorta via the ductus, which is not radiopaque and which enters the pulmonary artery In cases *with* pulmonary hypertension, there exists a *reversed shunt* from the pulmonary artery to the aorta and both vessels are rendered radiopaque simultaneously The anteroposterior view is the best projection. In addition, indirect signs may be found, for instance, enlargement of the pulmonary artery trunk, increased pulmonary blood flow, etc

Eisenmenger Complex. The silhouette of this cardiopathy is characteristic. In the plate, an intensely opaque right ventricle (as well as the aorta and its branches) is plainly seen. In some instances, the pulmonary artery appears with normal diameter, in other cases, it appears more or less dilated as it arises from the ventricle The pulmonary branches can be either normal or dilated

Ebstein's Disease. In a dextroangiocardiogram, the frontal projection shows the right-

innominate veins, superior and inferior venae cavae, etc.

2. Situation, size, and shape of *the right atrium and ventricle*, thickness of their walls, etc.

3. *Arteries* arising from the right ventricle or overriding the septum. These arteries could be the pulmonary, the aorta, or both. From this vessel or these vessels and their branches, the following data can be obtained: origin, number, caliber, course, and existence of *anomalous* communications that might occur between them.

4. *Interatrial* and *interventricular septal abnormalities.* When the blood pressure within the right cavities is greater than that within the left chambers, *a right-to-left shunt* may be demonstrated.

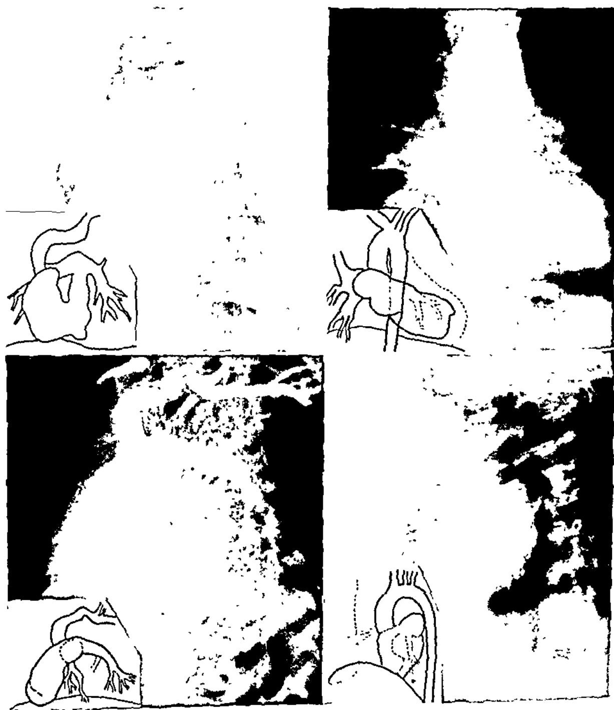


Fig. 4-100. Normal angiocardiograms (frontal view) Upper left, dextroangiocardiogram Upper right, levoangiocardiogram. Lower left, dextroangiocardiogram (LAO). Lower right, levoangiocardiogram (same projection).

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Ebstein's Disease. In a dextroangiocardiogram, the frontal projection shows the right-



Fig. 4-101. Pulmonary stenosis (lateral view). Upper left, *dextroangiocardiogram* showing the radiopacification of the superior vena cava and of the *right atrium.* Upper right, in a view ½ sec later, the jet is seen through the stenotic valve. Lower left, there exists, at this moment, a complete outline of the pulmonary artery trunk and of its *branches.* Lower right, in the levoangiocardiogram, the left cardiac cavities and the aorta are visualized.



Fig 4-102. Tetralogy of Fallot. Upper left, simultaneous filling of the aorta and of the pulmonary artery in the dextroangiocardiogram Upper right, the contrast of both arteries is marked Lower left, the pulmonary veins and left atrium appear slightly contrasted in the levoangiocardiogram. Lower right, no contrast medium can be observed 1½ sec later.

to-left shunt via the atrial septal defect, and later, a refilling image, i.e., an opacification of all four cardiac chambers. The image outlines best three chambers: the enlarged right atrium, the right ventricle, and the left ventricle.

Transposition of the Great Vessels. The diagnosis of this malformation is greatly helped by the dextroangiocardiogram (Fig. 4-103). Castellanos and Pereiras described the following four anatomoangiocardiographic types of this malformation.

Type 1. This brings to mind the image of the tetralogy of Fallot. The aorta has the same position and follows the same direction. Little or no radiopaque substance is seen within the left ventricle and, generally, the pulmonary artery is not seen. It may be difficult to differentiate from the tetralogy of Fallot if there is marked pulmonary atresia. Cooley and coworkers, in such cases speak of "pseudotruncus arteriosus."

Type 2 This is similar to type 1, but the aorta arises near the midline and goes backwards and slightly to the left to override the left bronchus.

Type 3. The aorta comes out slightly to the left of the midline From here, it goes upwards to the left margin of the cardiac silhouette, and bends over the left bronchus. The ascending portion of the aortic arch forms an outward convexity at the midarch of the left margin of the cardiac outline The descending aorta is seen at the center of the cardiac outline, between the termination of the superior vena cava and the origin of the aorta Whenever the pulmonary artery is seen, it is situated behind and inside the aorta.[1]

Type 4. The aorta arises far to the left of the midline and goes diagonally upwards and to the right to override the right bronchus, this reveals the existence of a right-sided aorta

Nonfunctioning Right Ventricle with Tricuspid Atresia. In most cases, for the diagnosis of this malformation serial dextroangiocardiograms are needed. In the first plates, one sees the filling of the right atrium, and almost immediately the passage of the radiopaque solution to the left atrium; the left ventricle is also seen. Soon afterwards, filling of the aorta and pulmonary artery takes place.

To determine the lack of filling-up of the right ventricle, the AP view is not as good as the LAO or the lateral views (Fig. 4-104).

Persistent Truncus Arteriosus Communis. In this type of anomaly, the aorta has a large, wide, lumen. In the cases studied up to the present, there is no filling image of the four cardiac cavities. The trunk of the pulmonary artery is not seen. However, in most cases, two arterial branches can be observed arising from the aorta; one going to the right lung and the other towards the left lung. Both branches are hypoplastic. The LAO view is of great importance for the visualization of the pulmonary arteries as they arise directly from the aorta (Fig. 4-100).

DATA GIVEN BY THE LEVOANGIOCARDIOGRAM

1. Number, diameter, position, termination, and other data concerning the pulmonary veins.
2. Situation, size, shape, and other characteristics of the left atrium.
3. Situation, size, shape, and other characteristics of the left ventricle.
4. Situation, origin, diameter, and other information about the aorta and its branches
5. Interatrial and interventricular septal abnormalities. When the pressure within the left cavities is greater than that in the right cavities, a left-to-right shunt may be demonstrated.

APPLICATIONS OF THE LEVOANGIOCARDIOGRAM

Anomalies of the Pulmonary Veins. Dotter and Steinberg found, in one patient, a large, abnormal pulmonary vein which descended through the right hemithorax and progressively increased in diameter, to end at the cardiohepatic angle Castellanos and Pereiras found, in cases with tuberculous infiltration, a compression of the pulmonary veins on the affected side

Lesions of the Mitral Valve. In all defects of the mitral valve, there is an enlargement of the left atrium.

Tumors of the Left Atrium or Ventricle. In a frontal projection, a filling defect due to the presence of a tumor can be seen Caseous

[1] Some American pediatricians and cardiologists did not accept the existence of type 3, in spite of the evidence given by means of anatomical specimens, until a similar case was described by Fanconi. About the same time, Goodwin, Steiner, and Wayne reported another case belonging to this type.

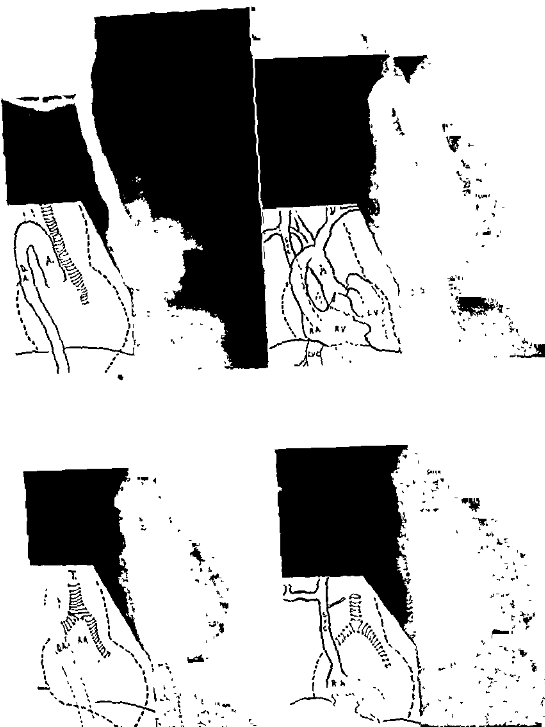


Fig 4-103. Total transposition of the great arteries (frontal view) Upper left, dextroangiocardiogram. The contrast medium is inside the right atrial cavity Upper right, sharp contrast of the aorta is visible at the extreme right Lower left, 1 sec later, there is much less contrast of the aorta Lower right, only a very small amount of dye appears in the aorta

cardiography with injection of CO_2 into the left ventricle, is a better method than that based on the use of a radiopaque substance.

Congenital Aortopathies. COARCTATION OF THE AORTA. The oblique view allows the visualization of the aorta, from its origin in the ventricle to the site of stenosis. Its diameter, its branches, and the internal mammary artery, are also seen.

PATENCY OF THE DUCTUS ARTERIOSUS. In lateral, left anterior, or oblique views, a dilatation of the aorta just at the site where the duct

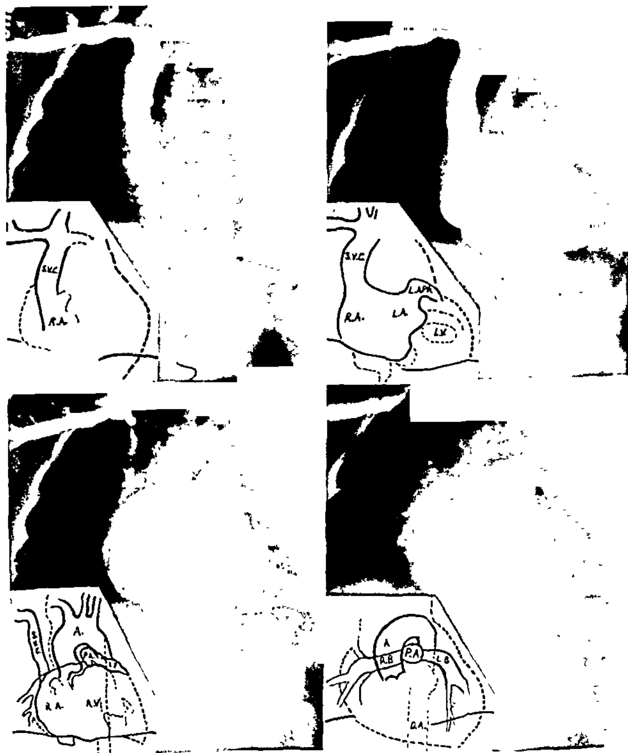


Fig. 4-104. Tricuspid atresia (frontal view). Upper left, only the superior vena cava is visible. Upper right, radiopacification of the left atrium and of the left auricular appendage. Lower left, contrast of the aorta and of the pulmonary artery. Lower right, the left ventricle is also visible.

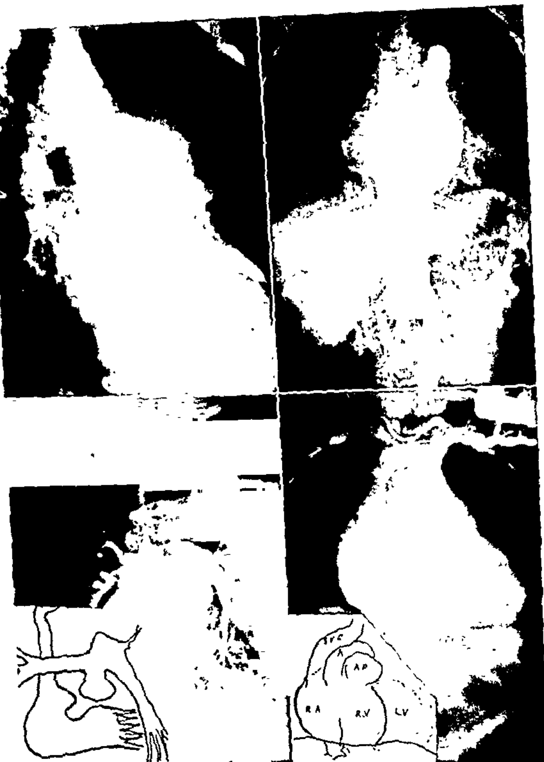


Fig. 4-105. *Upper left,* patent ductus (RAO) In the levoangiocardiogram, the pulmonary artery is visualized via the ductus. *Upper right,* absence of the inferior vena cava (frontal view). The injection, which was performed through the internal saphenous vein, shows the venous blood of the lower extremities ending in the left superior vena cava *Lower left,* infundibular pulmonary artery stenosis; a filling defect exists at the level of the stenosis *Lower right,* Ebstein's disease (dextroangiocardiogram, frontal view, taken immediately after the injection). The left atrium and the left and right ventricles are visualized.

originates, can be clearly seen. This was described by Sussman et al. (1943). It is possible to see, besides opacification of the aorta, a contrasted pulmonary artery. This was called "pulmonary artery image in aortic phase" by Narno et al. (Fig. 4-105).

RIGHT-SIDED AORTA. In the frontal view, there is visualization of the aorta and its arch going upwards and towards the right, to override the right bronchus.

DOUBLE AORTIC ARCH. In the AP view, there is visualization of both aortic arches surrounding the trachea.

Aortic Aneurysms. In this condition, the radiopaque substance goes through the aneurysmal sac, producing partial or total opacification.

Extrinsic Compression of the Aorta. In some instances, posterior mediastinal tumors are the cause of this condition. A narrowing of the vessel is clearly seen in the LAO view.

Torsion of the Aorta. The radiographic plate gives a clear image of the anomalous aorta. This condition happens in the severe dextroversions, and in cases of giant lung cysts, in which the heart is displaced to the right, with a clockwise torsion.

Intracardiac Shunts. INTERATRIAL SEPTAL DEFECT. Cases without pulmonary hypertension with a large left-to-right shunt have normal dextroangiocardiograms In the levo phase, there appears a typical image which has been called "refill or cast image" In such cases all four chambers are opacified together with the aorta, and the pulmonary artery trunk and its branches. The aorta is hypoplastic, and the pulmonary artery is large.

INTERVENTRICULAR SEPTAL DEFECT. In the majority of dextroangiocardiograms, there are indirect signs of some value. The most frequently seen is a blurred aspect of the infundibulum or conus. This is due to the mixing of the normal with the radiopaque blood coming from the left ventricle. In the levo phase, opacification of the pulmonary artery can be seen and differential diagnosis from a patent ductus may be very difficult. The greater the shunt, the more accentuated the contrast of the pulmonary artery trunk. When the left-to-right shunt is small and the cardiac outline is normal in size, both the dextro- and the levo-angiocardiograms are normal.

DIFFERENTIAL DIAGNOSIS OF CARDIOVASCULAR AND EXTRACARDIOVASCULAR SHADOWS

Angiocardiography is of value in distinguishing the normal cardiovascular image from the following structures: hypertrophied thymus gland, thymomas, tumors of the mediastinal lymph nodes, teratomas, coelomial cysts of the pericardium, neurogenic tumors, lipomas, fibromas, and vascular tumors.

There are other vascular images very difficult to evaluate without the aid of this method, such as: aneurysmal dilatation of the pulmonary trunk or branches, especially those of the right side; pulmonary arteriovenous fistulas, aneurysms of the aorta, and aneurysms of the left and right azygos veins.

THORACIC AORTOGRAPHY

Thoracic aortography is the radiological visualization of the thoracic aorta and its branches by means of a radiopaque substance.

HISTORY

Nuvoli (1936) was able to opacify the aorta by the direct injection of 100 per cent sodium iodide into the aortic arch of an adult Castellanos and Pereiras (1938) created and introduced clinical aortography as a safe and routine method. They used the expression "retrograde aortography," to indicate the visualization of the aorta by injection of a contrast medium through a peripheral artery Radner (1948) injected a radiopaque solution through a catheter introduced into the brachial artery. In the same way, Freeman used the left common carotid artery. Gomez and Meneses Hoyos again applied Nuvoli's method, while Jonsson favored the percutaneous puncture of the aorta (Fig. 4-106).

TECHNIQUE

Anesthesia. Only barbiturate sedation is needed when injecting through a trocar or through a catheter using the brachial artery When using the carotid artery, general anesthesia is preferred, especially in older children

Equipment. When the left humeral artery is injected, Lindemann B-D, No. 18, 16, and 14 trocars are used However, the carotid artery permits the use of larger trocars, such as B-D 14 and 12. Standard B-D syringes can be used, except when



Fig 4-106. Upper left, normal aortography (LAO). The injection was performed through the left common carotid artery Upper right, coarctation of the aorta, "infantile" type The contrast medium, which was injected through the left common carotid artery, clearly outlines the coronary as well as the collateral arterial circulation proximal to the stenosis. Lower left, patent ductus. Lower right, atypical ductus (frontal position)

dealing with a No. 12 trocar. When Cournand's or Lehmann's No. 6, 7, or 8 catheters are used, special injection devices are needed.

Arterial Reconstruction. The artery should always be reconstructed. In the case of the left humeral artery, the vessel should be sutured with 5-0 silk, especially in small children and newborn infants, and even if the trocar is introduced after the emergence of the deep humeral artery. Ligature of the carotid artery should be avoided but it can be done, when absolutely necessary, without complications.

Concentration. As a rule, a 50 per cent concentration of the radiopaque medium is sufficient.

Duration of the Injection. It should never exceed 1 sec.

Volume to Be Injected. An average of 1.5 ml/kg body weight is the volume to be injected.

Position of the Patient. This depends on the malformation to be investigated. The LAO position is the most appropriate for patients with patent ductus arteriosus and coarctation of the aorta. The frontal view is the first choice in patients with right aortic arch with anomalies of the great vessels and left root of Arkin, as well as those who have right subclavian arteries arising from the left side

Radiological Equipment. Aortography requires a more rapid plate changer than the one used for angiocardiography With seriographs operating at 2 plates/sec, the patent ductus arteriosus is hardly visible, especially in newborn infants As a rule, a seriograph taking 6 plates/sec is indispensable for a proper diagnosis of this malformation Coarctation can be visualized with less rapid machines The ideal equipment is a biplane, with a 500 ma generator, operating at 6 plates/sec However, a highly trained team can obtain perfect films with less rapid single-plane seriographs, especially in older children and adults A presumptive diagnosis usually helps to obtain a proper radiological technique and consequently clearer images

ACCIDENTS

Extravasation. This occurs when a needle, instead of a catheter, is used

Right Hemiparesis. This has been observed in patients in whom the left carotid artery was used, it always disappeared in a few days

Pneumothorax. This may occur if the common carotid incision is made too low This complication, however, does not produce symptoms, and the diagnosis is possible only by means of x-ray

Convulsions. These have been reported in some cases in which the concentration of the radiopaque solution used was greater than 70 per cent.

Absence of Radial Pulse. This was noted when the humeral artery was not properly reconstructed In some cases, the pulse did not reappear until 2 to 5 days later.

Sudden Death. This is exceptional at the moment of injection, if the rules and precautions outlined above are closely followed.

CONGENITAL AORTOPATHIES

Patency of the Ductus Arteriosus. A levoangiocardiogram aids in the diagnosis of this condition because the opacification of both the aortic arch and the pulmonary artery and its branches is demonstrated. However, accurate diagnosis could be difficult in the presence of a narrow duct giving a small shunt. In patients with interatrial or interventricular septal defect, a levoangiocardiogram gives a well-contrasted aorta, but sometimes both septal anomalies coexist. Retrograde aortography is of greater value because it allows a direct diagnosis through visualization (on a radiographic plate) of the ductus arteriosus, even when the shunt is slight. In cases of extreme tetralogy of Fallot (pseudotruncus), the two pulmonary branches can be seen arising from a patent ductus arteriosus of varying length and width.

Aortopulmonic Septal Defect. In this type of aortopathy, the radiopaque substance flows from the aorta to the initial portion of the pulmonary artery. It requires an ultrarapid seriograph (six or more plates per second) or cineaortography.

Vascular Rings. Aortography offers a highly contrasted image of the vessels, which sometimes cannot be obtained from ordinary levoangiocardiograms.

Aortic Insufficiency. Variable quantities of the radiopaque solution flow into and appear in the left ventricle. This does not occur in cases of vascular rings or in cases with normal aortic cusps

Coarctation of the Aorta. With good technique, a levoangiocardiogram may show the exact caliber of the aorta, therefore, it has great diagnostic value. However, retrograde aortography gives a better image and reveals the precise, minute, and all-important anatomical details so necessary for the correct surgical treatment of this anomaly.

Aortic Kinking. Nine cases of this condition have been reported The abnormal configuration of the aorta can be clearly seen in the

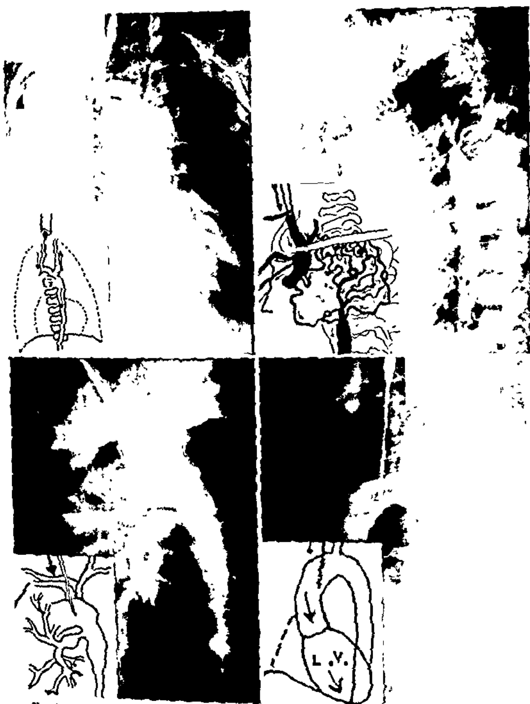


Fig. 4-107. Upper left, *Taussig-Blalock* anastomosis (frontal view). The injection was performed through *the right* common carotid artery. *The artificial fistula* is closed. Upper right, complete interruption of the *aortic arch (LAO)*. The ascending and the descending aortas are connected by collateral channels. Lower *left, truncus arteriosus* communis (LAO). Both pulmonary arteries arise from the aorta through a *short and narrow ductus*. Lower right, acquired aortic insufficiency (LAO). The injection was performed through *the left common carotid* artery and shows the contrast medium inside the cavity of the left ventricle.

frontal and left anterior oblique positions. The difference from coarctation is easily ascertained.

Anomalies of the Lumen of the Aorta. Both hypoplasia and dilatation of the aorta are easily diagnosed by means of both levoangiocardiograms and retrograde aortography.

Anomalies of Position and Number. As a right-sided aorta and a double aortic arch can be diagnosed by levoangiocardiography, there is no advantage in using aortography for this purpose.

Anomalies of the Aortic Branches. When the aorta comes off the right ventricle, the branches of the aortic arch appear more contrasted in the dextroangiocardiogram than in the levoangiocardiogram. However, as the contrast of the great vessels in levoangiocardiograms is not as elegant as desired, a definite diagnosis cannot be made accurately. In the case of arteries arising from the arch, following an anomalous course, and producing "dysphagia lusoria," a retrograde aortogram is imperative The same is true when data on the caliber and origin of the great vessels of the aortic arch are needed.

Aneurysms of the Sinus of Valsalva. Ruptured aneurysms of the sinus of Valsalva have been reported in several publications. Aortography allows the visualization of the radiopaque substance flowing from the site of rupture to the corresponding cardiac chamber.

Truncus Arteriosus Communis. In cases with total persistence of the truncus arteriosus, the arteries going to the right and left lungs arise separately from this trunk. As neither dextronor levoangiocardiograms are dependable for a correct diagnosis, retrograde aortography is one of the most valuable procedures for the recognition of this malformation.

Surgical Anastomosis. The permeability of a Potts-Smith or a Taussig-Blalock anastomosis *cannot* be ascertained by angiocardiography. This is due to the dilution of the radiopaque substance in the cardiac chambers and to the superimposition of different structures. Conversely, aortography produces perfect contrast. When the surgical opening is patent, the images corresponding to the pulmonary artery and its branches are also seen, allowing an evaluation of the magnitude of the shunt. This also is possible in the terminoterminal anastomosis of a subclavian with a pulmonary artery (Fig. 4-107).

ACQUIRED AORTOPATHIES

Aneurysm. The diagnosis can be established by both levoangiocardiography and retrograde aortography.

External or Extrinsic Compression. Retrograde aortography is the method of choice for the diagnosis of this condition

Torsion. Again, retrograde aortography is the method of choice. This condition is seen in the severe acquired dextrocardias.

PERIPHERAL ARTERIOGRAPHY, AORTOGRAPHY, AND VENOGRAPHY

Although the first successful clinical visualization of a peripheral artery was achieved in 1923 (Berberich and Hirsch), it was not until safe organic iodides were introduced that use of this clinical tool gained impetus With the direct surgical approach to diseased arteries in particular, safe, accurate, and simple methods of radiological visualization of the peripheral arteries has become absolutely necessary Hardly a vascular system in the human body has escaped exploration but in this brief section it is proposed to limit the discussion to aortography and arteriography and venography of the limbs. More detailed surveys of modern methods and techniques can be obtained by consulting the review of Lindbom and the text on peripheral vascular disorders by Martin, Lynn, Dible, and Aird (1956).

INDICATIONS FOR ARTERIOGRAPHY AND AORTOGRAPHY

When clinical examination suggests or confirms the presence of arterial insufficiency or overt obliteration, radiological visualization of the vessels assist in the following ways.

1. It accurately demonstrates the presence of arterial disease
2. It exactly delineates the level and extent of the arterial block.
3. It demonstrates the degree of collateral circulation around the diseased segment.
4. It outlines the state of the vessels proximal and distal to the thrombosed portion.

The information thus gained may help to diagnose the cause of the obstruction, the feasibility of a direct surgical attack on a major

diseased artery may be ascertained; the advisability or inadvisability of sympathectomy in Raynaud's disease may be determined; and, also, a guide to the optimum level of an amputation may be obtained. Also, peripheral arteriography and aortography are valuable in the diagnosis and intelligent approach to the treatment of aneurysms of the peripheral arteries and the aorta. To a lesser extent the procedures may be of use in arteriovenous fistulas and in the differential diagnosis of vascular tumors of soft tissue and bone, such as sarcomas and hemangiomas.

TECHNIQUES AND CONTRAST MEDIA

Briefly stated, 30 ml of 50 per cent *Diodone* (*Diodrast, Pyelosil*) outlines the femoral artery and its branches, 15 ml of 50 per cent dye outlines the brachial artery and its branches, and 50 ml of 70 per cent dye delineates the aorta and the upper femoral arteries. *Thorotrast* may be used but is not advised in the younger subject since it is radioactive and is not excreted from the body but permanently fixed in the reticuloendothelial system. There is no contraindication to its use in the elderly patient when the life expectancy is less than the period necessary for an induced malignancy to develop, i.e., about 20 years. If Thorotrast is used, no sensitivity test need be performed, nor is this necessary if an organic iodide is used with general anesthesia, but if iodides are to be used with local anesthesia alone, a procedure which is not recommended, the patient should be tested for sensitivity to the particular iodide preparation by the intravenous injection of 2 ml. Tachycardia, coughing, salivation, or the appearance of a rash are signs of sensitivity, and desensitization must be carried out before arteriography can be safely performed (Goodwin et al.).

Arteriography and aortography should be performed under light general anesthesia supplemented by a short-acting relaxant, i.e., succinylcholine, given immediately prior to the injection of the dye. General anesthesia is preferable because it (1) avoids pain, (2) prevents movements produced by pain, (3) prevents the uncomfortable feeling of warmth and the vasovagal symptoms accompanying aortography, and (4) promotes maximal peripheral vasodilatation, thus avoiding confusion between organic lesions and vascular spasm.

Percutaneous puncture of the vessels is preferable, because exposing an artery for arteriography converts a simple procedure into an operation. In many hundred arteriograms the author has never had to resort to open exposure of an artery. While elaborate methods and expensive equipment are available, perfectly good arteriograms can be obtained by the simple methods to be outlined. But these must be practiced by the radiographic team so that timing is perfect.

Lower Limb. Visualization of the femoral artery and its branches is the most frequently required arteriogram. This is only taken when the femoral artery is palpable at the groin. If it is not palpable, or pulsation is very faint, an aortogram is necessary.

The limb is placed on a plywood cassette tunnel with the limb externally rotated to project the arteries away from the bones. Two 14 by 17-in. cassettes are placed in the tunnel with tapes applied to them and additional cassettes are held in readiness. The femoral artery is entered percutaneously just below the inguinal ligament using a short-bevel No. 18 needle and a 30-ml syringe containing 50 per cent dye. Once the lumen is cleanly entered, as evidenced by a good jet of blood back into the syringe, the dye may be rapidly injected against the blood stream and the artery is then compressed until a second or even a third set of exposures has been made. The first set of x-rays is taken when two-thirds of the medium is in and the rest of the exposures are made as quickly as possible. If an assistant is available, proximal compression of the artery while the injection is being made and the films are taken will similarly prevent too rapid dilution and passage of the contrast medium through the vessels of the limb. After the needle is withdrawn, firm pressure over the puncture site for 3 to 5 min will prevent formation of a hematoma. By the above technique, as many as six exposures can be made and the vessels of the whole limb, including the foot, can be outlined in 20 sec.

Upper Limb. It is seldom necessary to visualize the vessels of the upper limb proximal to the elbow, but it is more usual to investigate the vessels of the forearm and the digital arteries of the hands, i.e., chiefly in Buerger's disease, and in order to differentiate Raynaud's disease from Raynaud's phenomenon.

The circulation to the limbs is controlled by a blood pressure cuff placed around the upper arm as for taking blood pressure. Again, with the patient anesthetized, the forearm and hand are placed palm up on a cassette tunnel made of plywood and are gently but firmly taped in that position with fingers separated and held thus with cellophane tape. Multiple exposures using 10 by 12-in. cassettes are made in the following manner. The brachial artery is entered by percutaneous puncture at the crease of the elbow joint, as it lies beside the biceps tendon, using a short-bevel No. 19 needle and 15 ml of 50 per cent dye in

a 20-ml syringe. Once the artery has been successfully entered, the blood pressure cuff is inflated to above systolic blood pressure, the contrast medium is rapidly injected, and the first film is taken. The cuff pressure is then lowered to diastolic level for one or two pulse beats and then reinflated, then a second film is exposed. This procedure is repeated five or six times, in order to obtain both arterial and venous phases of the blood flow.

Aorta. Since only the abdominal aorta and its pelvic branches come within the realm of the peripheral vascular surgeon, only abdominal aortography will be discussed. Introduced by dos Santos, *translumbar aortography* is now the procedure of choice for visualization of the abdominal aorta, the iliac arteries and the upper portions of the femoral arteries.

Under general anesthesia, and intubated to ensure respiratory control, the patient lies prone on the cassette tunnel which has been fitted with a stationary grid. A preliminary x-ray film is taken to confirm the patient's position and the radiographic technique. The aorta is entered by passing a 6-in. No 16 needle, provided with a two-way tap for flushing with heparinized saline solution, upward and medially beneath the 12th rib from a point a handsbreadth lateral to the 1st lumbar spine If the needle impinges on the vertebral body or a transverse process, it is gently withdrawn and manipulated past these structures until *it just slides by the 12th thoracic vertebral body.* The needle will be felt to enter the aorta and blood will stream back into the syringe containing heparinized saline solution The needle is then clamped and held in position with a hemostat, the two-way tap is turned to admit the contrast medium and 50 ml of 70 per cent dye is injected mechanically or manually as rapidly as possible. Three 14 by 17-in. films are exposed in succession, the first when two-thirds of the dye is in and the other two as quickly as possible thereafter

Retrograde aortography is seldom used but may be indicated in order to visualize abdominal aneurysms when direct puncture may be hazardous. The preferred method is to pass a polyethylene tube or No. 9 cardiac catheter up the radial branch of the brachial artery and then down the aorta to the appropriate level, where the dye is injected and the films subsequently exposed In this procedure, the patient is supine and the radial artery is exposed and entered a handsbreadth distad to the crease of the elbow joint As an alternative, the brachial artery may be entered in the arm and polyethylene tubing threaded into it through a large-bore needle and then up into the aorta as before.

COMPLICATIONS

The precipitation of local or distal arterial thrombosis is the most serious complication of arteriography but occurs very rarely. The author has never encountered it personally but, if 70 per cent dye is used in a limb, *thrombosis* and *gangrene* may occur. Repeated attempts at percutaneous puncture may traumatize an artery and precipitate *thrombosis* The dislodging of atheromatous plaques in cases of peripheral embolism of the artery, and the development of an arteriovenous fistula have also been reported as complications but have not been personally seen. Hematoma formation at the site of puncture, extraluminal extravasation of contrast medium and inaccurate placement of the needle with a partial intramural injection, are the commonest complications but, although a source of discomfort to the patient, they never cause permanent damage. If there is a hematoma, application of local heat and injection of saline solution containing hyaluronidase into the surrounding tissues speed absorption of extravasated blood and contrast medium and decrease local reaction.

Similar complications may arise after aortography but, apart from an occasional persistent backache and a rare paralytic ileus, no harm has come from paraaortic extravasation of dye. Precipitation of *thrombosis* in the aorta is rare but leakage of an abdominal aneurysm has been seen by the *author due to the injudicious* use of translumbar aortography to visualize an abdominal aneurysm. Transient *anuria* has been reported from injection of the medium into the renal artery, but the author has not seen this nor has he encountered *gangrene of the intestine* due to accidental injection into the superior mesenteric artery. It is probable that these complications are the result of intramural injection and dissection of the aorta as reported by Gaylis and Laws and not due to the dye itself. The author has produced a tension pneumothorax by puncturing the left lower lobe of the lung in attempting to get well above the renal arteries. *Paraplegia,* the rarest but most serious complication of aortography, has been reported, probably as a result of thrombosis of vessels to the spinal cord

On the whole, arteriography and aortography are safe procedures and serious complications are rare Neither procedure should, however, become a "routine" investigation but should only be used when the information they may supply is necessary for proper evaluation and intelligent treatment of the patient.

INTERPRETATION OF ARTERIOGRAMS AND AORTOGRAMS

Normal Appearance. Distal to the injection site, the vessels will be clearly outlined, the vessel walls will be smooth and parallel, and the caliber of the arteries will gradually diminish towards the periphery. In the thigh, the superficial femoral and profunda arteries fill, but their muscular and cutaneous branches are insignificant (Fig. 4-108). The geniculate anastomosis around the knee is seen and the popliteal artery and its three branches are identified. Thus, in the calf, the anterior and posterior tibial arteries and the peroneal artery will be identified In the foot, the dorsalis pedis and plantar vessels may be outlined and, by this time, venous filling will be apparent

In the upper limbs, similar visualization of the major arteries peripheral to the site of injection will be noted The radial, ulnar, and interosseus arteries will be seen. The palmar arch and the digital vessels to the fingers and the pulp spaces are usually demonstrated (Fig 4-109) Again, muscle and cutaneous vessels are insignificant. In short, the normal vessel presents a smooth uniform lumen and a direct course with a minimum number of collateral vessels

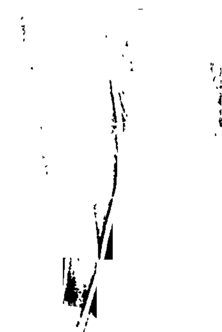


Fig. 4-108. Normal femoral arteriogram



Fig. 4-109. Normal arteriogram of hand. (From R B Lynn et al. Lancet, 1955)

Abnormal Appearance. The early signs of obliterative vascular disease are slight irregularities in the vascular walls (Fig. 4-110), narrowing of the origins of the major branches of the vessel, and the appearance of extensive

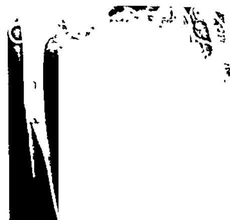


Fig. 4-110 "Ragged" irregular femoral artery in nonobstructed atherosclerotic patient The irregularities correspond to the calcified plaques so well shown in the opposite limb

a 20-ml syringe. Once the artery has been successfully entered, the blood pressure cuff is inflated to above systolic blood pressure, the contrast medium is rapidly injected, and the first film is taken. The cuff pressure is then lowered to diastolic level for one or two pulse beats and then reinflated; then a second film is exposed. This procedure is repeated five or six times, in order to obtain both arterial and venous phases of the blood flow.

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Fig. 4-114. A. Translumbar aortogram showing a "ragged," tortuous aorta, left common, and external iliac arteries. The left internal iliac artery is almost completely obstructed and there is no filling of the right iliac vessels. B. Aortogram showing complete obliteration of the aorta immediately below the renal arteries. C. Aortogram showing distortion of the abdominal aorta and the soft tissue shadow of a large abdominal aneurysm.

small arteries, collateral circulation is most frequently carried out by a process of lateral branching, terminal branching, or arborization. As the disease advances, the main artery may be completely occluded and the efficiency of the distal circulation will depend upon the number, size, and site of the collateral vessels (Fig 4-111). If the distal vessels fail to fill and venous filling is delayed or absent, a poor circulation is indicated.

With minor exceptions, the above description fits obliterative vascular disease whether it be atherosclerosis or thromboangiitis obliterans. There is no constant pattern which is precisely diagnostic but there are certain differences between various peripheral vascular diseases. Thus a *moth-eaten, patchy appearance of the lumen* with block of a major artery is more characteristic of atherosclerosis. In Buerger's disease, the peripheral arteries, usually patent in atherosclerosis, are nearly always obliterated while the major arteries above the diseased segments are relatively normal until the disease is very advanced. When major arteries are initially involved in Buerger's disease, the appearance of the block is indistinguishable from that in atherosclerosis, but the major artery above the block does not have the irregular appearance of the vessels in atherosclerosis. It may be narrowed but the narrowing is smooth and uniform (Fig 4-112).

The appearances in the upper extremity are similar to those in the legs, however, disease here is rarely atherosclerotic, but usually Buerger's or Raynaud's disease. In Raynaud's disease, the digital arteries are obstructed, and collateral vessels are small and rarely reestablish an efficient circulation distal to the blocks. The arteries of the palmar arch are never involved in Raynaud's disease but may be blocked, as may the radial and ulnar arteries at the wrist in Buerger's disease.

In aortography, atheromatous changes of varying degree may be demonstrated in the aorta and iliac vessels. These vary from partial obstruction of one iliac artery (Fig 4-113) to complete obliteration of one iliac artery and disease of the other (Fig 4-114A), to complete obliteration of the abdominal aorta as high as the renal arteries (Fig 4-114B). Extensive col-



Fig. 4-111. Full length femoral arteriogram in a patient with "peripheral" Buerger's *disease shows* the relatively normal femoral and popliteal *arteries,* thrombosis of the posterior tibial *artery at its origin,* thrombosis of the anterior tibial artery at the ankle joint, and poor vascularization of the foot. *Similar* changes were seen in the opposite limb—a *situation* often encountered



Fig. 4-112. Femoropopliteal thrombosis with good collateral circulation filling the popliteal artery in patient with Buerger's disease. Note the "tailing-off" of the femoral artery and the normal appearance of the vessel above the diseased segment.

collaterals among the muscular and cutaneous vessels. These vessels, which normally do not fill, show up characteristically as tortuous arterial channels pursuing irregular wandering courses and reentering major vessels distal to an arterial block. They may be as large as the main vessel and carry sufficient blood to permit good visualization of the distal vessels. In the



Fig. 4-113. *Aortogram* showing early changes appearing *in atherosclerosis* Note the "nipping" of the right *common iliac artery,* the left internal iliac artery, and the *absence of filling* of the right internal iliac artery.

nonfilling of a deep vein does *not necessarily* imply that the vein is thrombosed. The only information a venogram can categorically give is that a vein that has been outlined is definitely patent.

Retrograde phlebography through the long saphenous vein exposed in the groin during high saphenous ligation was the technique originally used by the author. This was then replaced by direct puncture of the femoral vein at the groin with injection of 35 per cent *contrast medium*. The best method, however, is the planograde route, injecting the dye as far distally as possible. Thirty-five per cent dye should be used, as stronger concentrations cause thrombosis of the veins. A sensitivity test must be made since the procedure is carried out without anesthesia in order to obtain the cooperation of the patient.

The patient lies supine with the leg on a cassette tunnel, and the x-ray table is tilted 15° into the foot-down position. A tourniquet is placed *immediately above the ankle joint to direct the dye* into the deep venous system. A vein on the dorsum of the lateral aspect of the foot is chosen and entered, by means of a No. 19 short-bevel needle and a syringe containing 30 to 40 ml of 35 per cent contrast medium. Fifteen to twenty milliliters of dye is rapidly injected and a 14 by 17-in. film is exposed to include the leg and popliteal fossa. The patient then performs the Valsalva maneuver while the remainder of the dye is being injected and two or three more films are taken *in order* to cover the upper leg and lower thigh and the thigh. A final picture is taken, *after* cessation of the Valsalva maneuver, to cover the thigh. It is important to *instruct the patient in the Valsalva maneuver and have him practice it beforehand*. By this means the contrast medium can be held in the veins for a considerable time, the communicating veins, if incompetent, will be made to fill, and the competence of the deep venous valves may be demonstrated. Without the Valsalva maneuver, valve competence cannot be *ascertained* (Fig. 4-115B). *Films can also be made with the* patient lying on his side to obtain views of the vessels in the lateral projection, but this is seldom done.

The interpretation of *venograms of the lower limbs* is confusing and often unreliable because *of the numerous* normal anatomical variations possible in the deep and superficial venous systems and their valves. With the above method, good visualization of the deep veins in particular can be achieved but the best that can be said of phlebography is that if a vein is outlined it is patent, while failure to fill does not *necessarily mean that the vein is thrombosed* or diseased (Fig. 4-115C). If a vein is well outlined and a well-performed Valsalva maneuver produces reflux of dye back down the vein without demonstration of *competent* valves, then these valves may be absent, congenitally, or as a result of previous deep venous thrombosis (Fig. 4-115D).

Phlebography of the upper extremity is rarely indicated but may be performed to *demonstrate an obstruction* of the axillary or subclavian veins.

The patient lies on a cassette tunnel or on an x-ray table and 20 ml of 35 per cent contrast medium is injected into an antecubital vein. The first film is exposed when 10 to 15 ml of the dye has been injected and the second film exposed at *the end of the* injection. Further films will show the collateral circulation around the shoulder girdle in axillary vein thrombosis.

lateral circulation through the mesenteric and lumbar arteries may reestablish a remarkable circulation to the limbs.

Arteriography and aortography may also be used to demonstrate the site and extent of aneurysms of the aorta (Fig. 4-114C) and peripheral arteries (Fig. 4-115A). If the renal vessels are involved, the surgical approach must vary from that used when there is no aneurysm. The localization of arteriovenous fistulas may also be aided by the use of these techniques.

Thus, visualization of the aorta and the major vessels to the limbs is a valuable procedure which provides information as to the site and extent of arterial occlusions, arterial aneurysms, and arteriovenous fistulas—information that can be gained by no other means. But it is a procedure requiring anesthesia, teamwork, and skill and should not be used unless the information it will give cannot be obtained by simpler means. The x-ray photographs must be interpreted by a member of the team who was present during the procedure, so that the technique and timing of the films are known lest erroneous deductions be drawn.

PERIPHERAL PHLEBOGRAPHY

Visualization of the veins of the extremities can be achieved by the injection of 35 per cent organic iodide solution into them. The information obtained and the results of phlebography are less valuable than those gained by arteriography. Since dos Santos introduced venography of the lower limbs, numerous methods have been described. No one method is completely satisfactory and the results are often unreliable. Therefore, the author proposes to mention only the methods which he has found best for the following purposes: (1) outlining the deep and superficial venous systems of the legs; (2) for demonstrating the communicating system between the two; and (3) for visualizing obstruction of the deep veins or valvular incompetence, since it is usually the deep veins and their valves that are of primary interest. From a purely diagnostic point of view, however, phlebography of the lower limbs has little to offer over clinical examination because



Fig. 4-115. A Arteriogram showing saccular aneurysm of the popliteal artery caused by a gunshot wound, note metallic fragments. B. Retrograde phlebogram in a normal subject showing good valve cusps and a patent vein but marked reflux which so often occurs with this technique even in the normal subject. C. Planograde venogram in a postphlebitic patient showing obstruction of a deep calf vein with filling of the long saphenous vein through a communicating vessel. D. Planograde venogram showing absence of competent deep valves by reflux during Valsalva maneuver.

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Evaluation of cardiac function by methods using the x-ray

Roentgen Kymography

PIETRO CIGNOLINI

Electrokymography: Technical Aspects

BERT R. BOONE AND FRANK W. NOBLE

Electrokymography: Practical Applications

ALDO A. LUISADA AND FELIX G. FLEISCHNER

Cineradiology

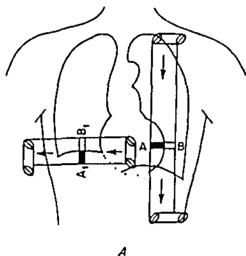
FRANK L. CAMPETI

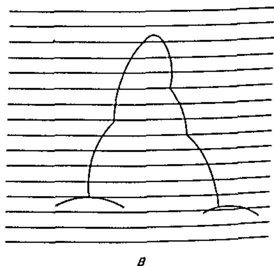
ROENTGEN KYMOGRAPHY

Roentgen kymography (RK) is a special roentgenographic technique which is used for recording the movements of the cardiac silhouette on an x-ray film. Numerous points of the silhouette can be explored by using grids with multiple slits.

HISTORY AND TECHNIQUE

Kymography (το κυμα = wave) is a word which was used in biological research before being used in roentgenology. The first study of roentgen kymography was that of Sabat (1911), who used a well-known schematic figure (Fig 4-116A). The





A B

Fig. 4-116. A. Principle of roentgen kymography. (*From Sabat*) B. The multiple-slit grid for plane roentgen kymography. (*According to Stumpf.*)

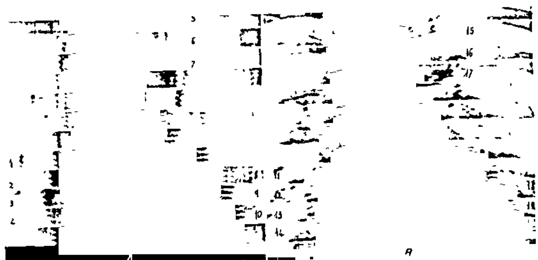


Fig 4-117 A Normal young woman. Plane roentgen kymogram with fixed grid. B. Same individual as in (A). Plane roentgen kymogram with movable grid.

following year, Gott and Rosenthal used the phrase "roentgen kymography" which subsequently came into common use.

Roentgen Kymography of Two (or Four) Points with Rapid Registration. The RK's of Gott and Rosenthal were recorded through a single slit. Later, Crane (1916) used a kymograph with two overlapping slits, limiting the movement of the film to the space between the fissures Scherf and Zdansky (1929) used a horizontal slit divided in two parts in order to be able to select different points at the right and left sides of the heart.

Roentgen Kymography of Several Points with Slow Registration The preceding techniques explored only a few points, with long tracings and high registration speed Stumpf (1928) described a new method which sacrificed the speed of registration in order to increase the number of points studied. This is "plane roentgen kymography" (PRK) The slits were numerous, one every 12 mm (Fig 4-116B) The movement of the film was limited to the space between two fissures. In order to register three cardiac beats within the 12 mm of the film, it was necessary to use a very low film speed, usually 4 mm/sec. *If the grid is fixed and the film is moved,* it is possible to obtain a record of the points intersected by the fissures (Fig 4-117A) If, on the other hand, *the film is*

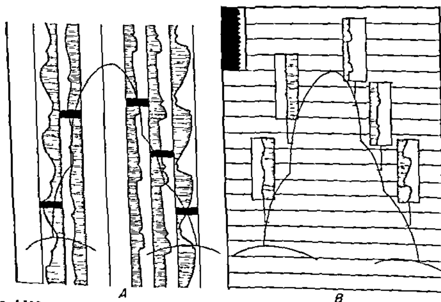


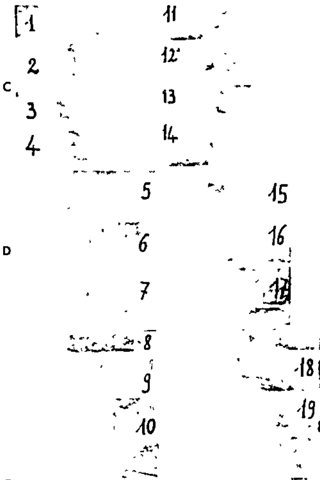
Fig. 4-118. A Analytic roentgen kymogram B Associated analytic and plane roentgen kymograms (polykymography) (According to Cignolini, 1950.)



A



B



C

D

E

RA LA LV F

Fig. 4-119. (Legend on facing page.)

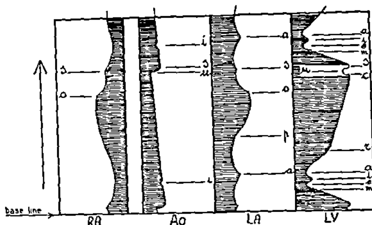


Fig. 4-120. Normal roentgen kymographic cycle.

fixed and the grid is moved, it is possible to explore in succession the movements of all parts of the contour (Fig. 4-117B).

Delherm et al (1934) modified Stumpf's grid ... 30 ... ntly ... who

Roentgen Kymography of Many Points with Rapid Registration. In 1930, the author described the technique of analytical roentgen kymography (ARK). The slits were limited to short segments at different levels of the cardiovascular silhouette, and the film speed was high (33 mm/sec) Sometimes it is possible to place a slit on each of the various arcs If this is not possible, subsequent films are taken, in an attempt to obtain various combinations The author used the technique of Fig 4-118A and also obtained records at 50 mm/sec (Fig 4-119A) As the load on the roentgen tube was too high and there was no reference to the cardiac shape and to the points from which the tracings were taken, the author later (1950) built a new model in which the analytic tracings were associated with plane roentgen kymography (Figs 4-118B and 4-119B).

PRACTICAL USE

Only plane RK (Stumpf) and analytic RK (Cignolini) are still in use The two methods have different purposes and complement each other Plane RK shows the basic form of the cardiovascular waves, ventricular, atrial, or vascular (Fig. 4-119C, D, E). Their recognition helps in the identification of the various arcs. Moreover, the amplitude of the waves can be evaluated.

An analytic RK shows the exact form of the waves, their amplitude, and the chronologic relationship between the pulsations of the various arcs. In Stumpf's method of kymography, there is a regular movement of the film or of the grid in the space between two slits (12 mm). The total movement takes place in 2.4 sec (5 mm/sec). In a subject with normal cardiac rate, a cycle is recorded in about 4 mm The kymograph of Stumpf may be rotated in any position However, the slits are placed horizontally for the study of the heart and vessels

Cignolini's apparatus has four tracks: the first and fourth are fixed, while the second and third are movable The grids, the film, and the shields are placed in their proper positions. The shields are metallic rectangles having at the bottom an arrow 50 mm long, during fluoroscopy, they are placed at different and correct levels In plane RK, on the other hand, they are placed in front of the film in order to avoid making a second impression of the previously recorded movements

Roentgen kymography is performed in three steps

1 *Fluoroscopy* with a 3-ft (90 cm) focal dis-

Fig 4-119. A Example of analytic roentgen kymogram B Example of associated analytic and plane roentgen kymography (polykymography) C Details of Fig 4-117 at natural magnitude Right atrium with fixed (1–4) and movable (11–14) grids. D Aortic arch with fixed (5–7) and movable (15–17) grids E Left ventricle with fixed (8–10) and movable (18–20) grids F Analytic kymograms of (B) at natural size.

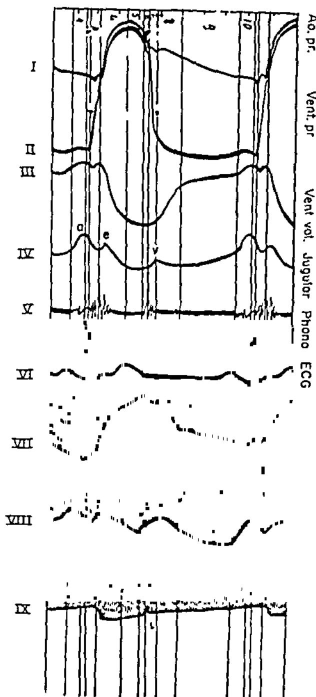


Fig. 4-121. Comparison of roentgen kymogram and *other records. I Aortic pressure. II. Ventricular pressure III Ventricular volume. IV. Jugular tracing.* V Phonocardiogram. VI. Electrocardiogram VII Roentgen kymogram L3. VIII. Roentgen kymogram. L2. IX. Roentgen kymogram: L1.

tance. The positions for the slits of the grid are selected on the screen, this grid is prepared at *the same time by moving the shutters.*

2 *Analytic kymography,* focal distance 90 cm (analytic grid in track I, film in track 2)

3 *Plane kymography,* focal distance 5 ft (150 cm), in the technique using movable grid, the film is in track 4, the shields in track 1, and Stumpf's grid in track 3. *In this way, both analytic* and plane RK are recorded on the same film. In order to avoid superimposition of cycles, the analytic tracings are shifted 50 mm higher than the real, and their arrows indicate the points of the cardiovascular edge from which they have been derived.

The Normal Cycle. An RK is read *from below upwards. One tip of a caliper is placed* on the base line of the tracing, the other on the wave under study. The RK shows graphically, better than any other method, the great variability of cardiac action, even in normal subjects. The study of the various segments of an RK tracing is easily made in young persons. The author has described (1934) the characteristics of the tracing in normal subjects (Figs. 4-120, 4-121).

PHOTODIASTOLE. Closure of the semilunar valves and the muscular relaxation cause an incisura between the systolic slope and the dicrotic wave. On the aortic and pulmonic arcs, the closure of the semilunar valves is shown by this *I notch.*

ISOMETRIC RELAXATION. Between the closure of the semilunar valves *(e)* and the opening of the AV valves *(a)* there is either a short segment or a longer segment including a small wave followed by a short flat line. This phase occurs before ventricular dilatation (isometric relaxation) The interruption of the flow causes an elastic vibration of 0 03 to 0.06 sec duration with an elevation of 1 to 2 mm of the contour. This vibration (as the *s* at the beginning of the systolic flow) can be seen in RK tracings of rubber models distended by a pump.

DIASTOLE. After the opening of the AV valves *(a)*, diastole occurs *(a-c)*, its speed is higher during the first third of the inscription The speed of the blood flow through the valves then decreases (diastasis, Fig. 4-123A). The best segment for the study of the left ventricle is the middle third of the left lower arc. The movements of the upper third of this arc, on the other hand, may give information about the action of the right ventricle. In fact, when this ventricle is enlarged and active, it pushes the ventricular muscle upward, one can observe large upward pulsations which are recorded in the horizontal slits as tall and sharp upstrokes.

ATRIAL CONTRACTION. The atrial tracing reaches the minimum atrial point *(o)* in about



Fig 4-122. Normal subject before exercise (A) and after exercise (B). After exercise an increase of the I and S waves is noticeable. C Tracing at normal size of the left ventricle; ECG is registered on the same film The I and S waves are well drawn.

0 06 sec, with a movement of about 2 to 5 mm, and remains at this level for 0 06 to 0 10 sec (Fig 4-123C).

PROTOSYSTOLE At a point between diastole and point c (tension), systole begins and the muscular fibers start contracting. This is the most important point of the RK cycle, and the only one with a constant position on the ventricular curve

ISOMETRIC PERIOD This is included between the closure of the AV valves and the opening of the semilunar valves, it lasts 0 02 to 0 08 sec (*c-u*). Its notch is from 1 to 3 mm deep.

OPENING OF THE SEMILUNAR VALVES (*u*). Most often, this corresponds to the lowest point of the *c-u-s* notch. The true position of *u* may be found by comparing this tracing with that of the aorta Because the velocity of the pres-

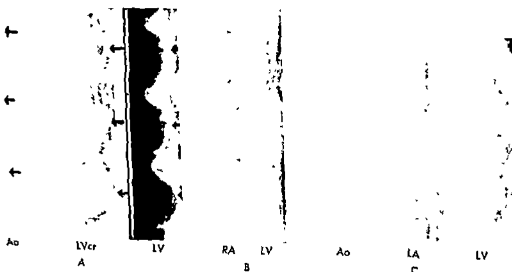


Fig. 4-123. A. Normal subject. The arrows over the LV tracings show the C wave, over the aorta, Ao, they show the beginning of systole B Left atrium recorded in LAO C Over the left ventricle, LV, the waves of rapid falling are broad (S and I waves) Over the left atrium, LA, atrial contraction is followed by small S and I waves transmitted from the ventricle Over the aorta, Ao, the incisura is broad

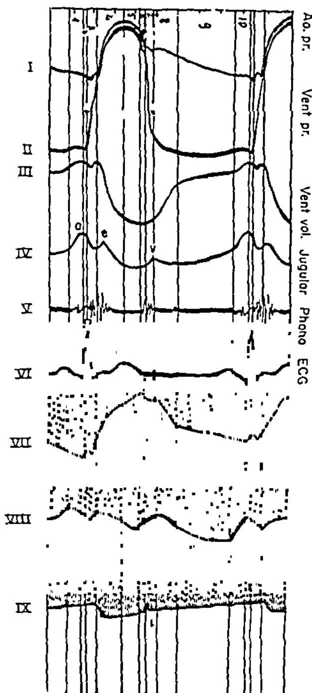


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sure wave is about 5 m/sec, the distance between the aortic valve and the point of registration on the aorta, divided by 50, will be equal to the hundredths of a second of the aortic delay over the opening of the semilunar valves.

RAPID EJECTION. Generally, *c* is the most outward point of the ventricular tracing but sometimes the point *s* may be higher than *c*, and actually so high that it looks like the final elevation of diastole. However, this fact might be the cause of errors in plane RK; in analytic RK, on the contrary, *c* is always recognizable, and is separated by a notch from the beginning of the *s* wave After rapid ejection, sometimes there are small vibrations on the systolic slope (*m*). The total duration of ejection varies with the rate, but is less than diastole. Atrial filling increases regularly during slow ventricular ejection. Frequently, large *s* waves are recorded on the atria. At the closure of the semilunar valves, the atrial curve shows a slight drop.

RIGHT VENTRICLE AND ATRIUM. Sometimes, in the lowest part of the right lower arc, a ventricular tracing is recorded (Fig. 4-124A). In general, right ventricular movements are predominant during most of the cycle, but atrial contraction is recorded in presystole.

ELECTROKYMOGRAPHY: TECHNICAL ASPECTS

The electrokymograph is an instrument developed for use with a conventional medical fluoroscope to produce detailed records of the motions of the heart borders or of the great vessels Through-and-through records of the pulsations in the cardiac chambers, great vessels, and even the lung fields may also be obtained.

The attempt to understand the complex mechanical activity of the heart has been intriguing investigators for many centuries William Harvey, in his animal experimentation on heart motions and functions, wrote. "I could not really tell when systole or diastole took place, or when and where dilatation or constriction occurred, because of the quickness of the movement."

Considerable progress has been made since Harvey's time and today, by means of animal experimentation, the physiological functions and motions of the heart are very well understood. However, clinicians and physiologists have a further desire to accurately record the motions of the human heart in its physiological

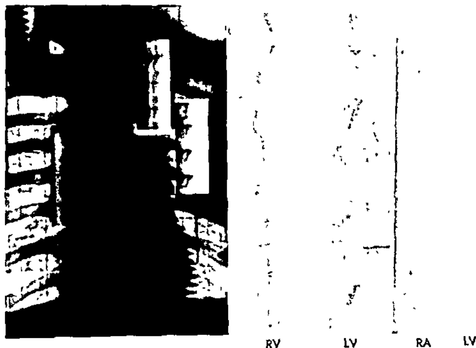


Fig. 4-124. A. The left ventricle, *LV*, and the right ventricle, *RV*, have almost the same tracing. B Over the right atrium, *RA*, the deep atrial systole and the movement transmitted from the right ventricle are seen (ventricular diastole and S and I waves).

habitat This desire arises from the well-established fact that each chamber of the heart and associated great vessels has its characteristic motion, and that this motion is altered in the presence of cardiovascular disease. The development of a method of permanent graphic recording of these motions in the intact human subject has been difficult to achieve, as the volume of literature indicates.

The visualization of the motions of the heart that became possible with the aid of roentgenoscopy suggested the possibility of applying the roentgen ray to some means of graphic recording of this motion. Sabat (1911) is credited with describing the first single-slit roentgen kymograph for this purpose. Crane (1916) was the original American pioneer in this field, and correlated his records with polygraphic and electrocardiographic curves. Knox (1925) developed a roentgen kymograph and pointed out its applicability not only in cardiology, but in the study of the diaphragm, stomach, and colon Katzman (1928, the United States) applied for a patent on a multiple-slit kymograph and kymoscope Stumpf (1931) described a multiple-slit kymograph and its application to the movements of various organs of the body. Hirsch and Schwarzschild (1934) amplified and extended the application of kymography and simultaneously recorded heart sounds to aid in record analysis and temporal relationships.

While considerable good work has been accomplished by this method, roentgen kymography has not become thoroughly established as a mandatory procedure in the examination of the heart. It seems that this is due to the analytical difficulties inherent in the fuzziness, smallness, and brevity of the recorded waves to be examined on the roentgen kymogram, the time-consuming nature of the analysis, and the difficulties of simultaneously recording, on the kymogram, curves of other cardiac events.

The recording of the fluctuation in ionization in an x-ray beam traversing a pulsating border represented one obvious way of improving on the roentgen kymograph This method was suggested and tried by Jacobi et al. (1932) Henny and Taft (1943) reported on the amplification and recording of the ionization current produced in a chamber back of a slit aperture aligned with the fluoroscopic x-ray silhouette The required high amplification and lack of stability became deterring factors Hjalmare issued a similar report on the use of a Geiger-Muller tube.

Heckman (1937) employed a photoelectric cell to convert the variations in light intensity occurring on the fluoroscopic screen. Marchal, and Liau and Minot, separately (1946) reported on similar applications of the photoelectric cell Posteli (1955) reported on an improved technique utilizing a selenium photoelectric cell.

Progress in electronic engineering subsequently made possible further advances in these attempts to record cardiovascular motion. The development of the 931-A type of photomultiplier tube, in particular, made possible the development of the electrokymograph by Henny and Boone (1945). Its subsequent modifications and applications were developed by the collaboration of Gillick, Oppenheimer, and Chamberlain. Luisada, Fleischner, and Rappaport contributed further (1948) modifications and application techniques.

Engstrom and Kjellberg (1949) described several changes in the electrokymographic apparatus designed to improve the frequency response and time delays in recording More recently (1954) Nordenstrom described an instrument, the Elema type Minograph 22, which uses two photomultiplier tubes, one behind the patient and the other in the usual position on the main fluoroscopic screen. The difference between the two tubes is applied to the recording apparatus. Subsequently, the authors independently developed a two-tube type, providing true d-c response with good stability and ease of handling

PRINCIPLE AND DESCRIPTION

The electrokymograph is an instrument designed to detect and record variations in the intensity of a beam of x-rays When the beam of x rays is directed past the borders of the heart or great vessels, the motions of these structures may be recorded. When the beam is directed through these structures, the cyclic changes in their density may be recorded

The electrokymograph consists fundamentally of a small roentgen radiation detector, its amplifier and power supply, and a recording device, such as an electrocardiograph. The radiation detector consists of a multiplier phototube with a small fluorescent screen

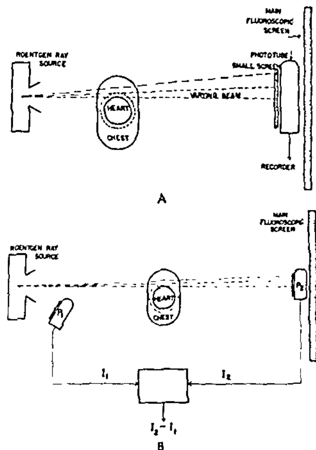


Fig. 4-125. A Schematic diagram of the standard electrokymograph. B Schematic diagram of a method for reducing drift in the electrokymograph caused by variations in the x-ray source.

placed directly over the phototube's sensitive surface. This detector unit is attached to the center of the patient side of the fluoroscopic screen of a conventional roentgenoscope (Fig 4-125A).

The detector unit is flexibly mounted for easy positioning over any heart border, permitting the moving border to act as a shutter or vane in the path of the roentgen rays arriving at the fluorescent screen of the phototube. The fluoroscopist can readily see both the cardiovascular silhouette and the detector unit through the main fluoroscopic screen

In recording tracings of *cardiovascular motions,* the radiation detector is centered roentgenoscopically over the border of the cardiovascular silhouette and the electrocardiographic recorder is set in motion. The pulsating heart border may be seen to cover an increasing proportion of the detector's fluorescent screen during the expansile phase of the cardiac cycle and a decreasing proportion of the screen during the contractile phase. The quantity of roentgen rays arriving at the detector's fluorescent screen thus varies in accordance with the motion of the heart border. The variation of these rays causes the emission of a varying amount of fluorescent light from the screen in proportion to their number. The phototube reacts to this light by generating an electric current proportional to the intensity of the fluorescent light. The recorder to which the phototube is connected produces a curve the amplitude of which is a function of the motion of the heart border under study.

In recording *density changes,* the detector is centered over the cardiovascular organ so as to exclude border motions. The intensity of the x-ray beam passing through the organ and falling on the radiation detector will vary in proportion with the anteroposterior thickening and thinning of the organ. The phototube, connected to the recorder, produces a curve the amplitude of which is a function of the varying density of the cardiovascular organ under study.

The evaluation and interpretation of an electrokymogram is greatly facilitated by the simultaneous recording of some other well-known cardiodynamic event. The carotid sphygmogram has been found to be satisfactory for most purposes, though a stethogram (phonocardiogram) or an electrocardiogram can likewise be used.

An early form of the electrokymograph consisted of a high voltage supply, a multiplier phototube, an electric filter, and a string galvanometer. The phototube was directly coupled to the galvanometer, and a bucking battery was used to subtract out the large d-c component of the photocurrent Since the percentage modulation of the x-ray beam is generally small, the base line adjustment and sensitivity controls were highly critical and interdependent The next step was to convert to capacitance coupling. This expedient removed the necessity of the bucking voltage and made the instrument much easier to operate Later, direct-writing electrocardiograph instruments were employed These instruments have the advantages of immediately available records and no photographic darkroom work

There are several deficiencies in the performance of certain commercially available electrokymographs. Since capacitance coupling is employed, it is not possible to interpret the records in terms

of exact positions of the heart border. The action of a coupling capacitor is to tend to make the average value of any input signal equal to zero. Thus, any change in the character of the heart motion will change the calibration of the record to some extent. The solution of this problem is to avoid capacitors and employ *direct coupling*. A second problem concerns the properties of the filter. This device performs the function of removing the mains supply ripple current from the phototube, while passing the current variations produced by the heart. Since the fundamental mains frequency is 60 cps, there will be ripple components at this frequency and all integral multiples thereof. The important frequencies contained in the electrokymogram extend from zero to at least 20 cps. It is therefore desirable to have the filter pass all frequencies from zero to as near 60 cps as is technically possible. A second feature of the filter is that it should produce a constant time delay, independent of frequency, throughout the passband. If the delay is not constant, the filter will distort the electrokymogram (EKy). A constant time delay implies that the phase delay in degrees is directly proportional to frequency. The filters which are employed in some of the commercial as well as many of the experimental electrokymographs are of the parallel-T rejection type, tuned to reject 60 cps and harmonics thereof. These filters have serious deficiencies in their frequency and phase response. They are band-elimination filters, so that they do not reject high-frequency noise. A low-pass filter having a passband from zero to 30 cps, a linear phase characteristic in this range, and high attenuation above this frequency, is easily obtained.

A third problem concerns the *instability* of the conventional x-ray machine. The x-ray tube is operated in a cathode-emission limited condition. Any variation of the cathode-emitting properties of the tube or any change in the cathode temperature such as might be caused by mains voltage changes will affect the intensity of the emitted x-rays. Since the phototube cannot distinguish between variations of illumination caused by the heart and variations caused by changes in x-ray emission by the roentgenoscope, it follows that any instability in emission of the x-ray machine will produce errors in the record. The problem could be completely solved if two phototubes were employed, one as a conventional electrokymograph, the other as a reference cell which simply monitors the emission of the x-ray tube. If a simple circuit were available which would accept the inputs from the two tubes and produce an output proportional to their ratio, variations in the x-ray tube would not affect the output. Unfortunately, no simple division circuit of this type exists. There is, however, a simple means of employing two phototubes in such a way as to minimize shifts due to changes in x-ray tube emission.

Referring now to Fig. 4-125B, assume a sinusoidal variation in x-ray emission at angular frequency ω_1

$$I_1 = A + B \sin \omega_1 t \tag{1}$$

and a sinusoidal modulation of this emission by the heart border at frequency ω_2. Thus

$$I_2 = I_1(C + D \sin \omega_2 t)$$
$$= (A + B \sin \omega_1 t)(C + D \sin \omega_2 t) \tag{2}$$

Now, use a simple arrangement to subtract I_1 from I_2, and arrange matters so that initially

$$I_2 = I_1 \quad \text{and} \quad \sin \omega_1 t = \sin \omega_2 t = 0$$

Then, from Eqs. (1) and (2),

$$\text{either } A = 0 \quad \text{or} \quad C = 1$$

Manifestly, the applicable solution is the second one. Then

$$I_{02} = I_2 - I_1 = D \sin \omega_2 t(A + B \sin \omega_1 t)$$
$$= I D \sin \omega_2 t \tag{3}$$

For the single phototube system, the output is simply I_2. From I_2, subtract A by means of a bucking battery. Then

$$I_{01} = I_2 - A = B \sin \omega_1 t$$
$$+ D \sin \omega_2 t(A + B \sin \omega_1 t) \tag{4}$$
$$I_{01} = I_1 D \sin \omega_2 t + B \sin \omega_1 t$$

The difference between the single- and the two-phototube systems is

$$\Delta = B \sin \omega_1 t$$

The maximum absolute value of Δ is B. Let full scale on the electrokymogram be $4AD$, corresponding to a peak-to-peak excursion of one-half the chart width. Then the maximum difference in base line shift between the two systems is

$$\epsilon_A = \frac{25B}{AD} \quad \text{per cent of full scale} \tag{5}$$

If the percentage modulation of the x-ray emission is defined as

$$P_1 = \frac{100B}{A}$$

then

$$\epsilon_A = \frac{P_1}{4D} \tag{6}$$

There will be some base-line shift which is common to both the single-tube and the two-tube systems. Equation (3) can be rewritten

$$I_{02} = AD \sin \omega_2 t + BD \sin \omega_1 t \sin \omega_2 t \qquad (7)$$

The first term is the desired term, while the second term is a shift-error term. The maximum possible absolute value of the shift term is BD. If, as before, full scale is defined as $4AD$, then the error common to both systems is

$$\epsilon_C = \frac{P_1}{4} \qquad (8)$$

The improvement to be expected through the use of the two-cell system is to be found from the ratio $\epsilon_\Delta/\epsilon_C$. In per cent this ratio becomes

$$I = \frac{100\epsilon_\Delta}{\epsilon_C} = \frac{100}{D} \qquad (9)$$

Since D is typically of the order of 0.1, one may expect an improvement of the order of 1,000 per cent in drift due to x-ray emission through the use of a 2-photoelectric-cell system with subtraction.

A second theoretical advantage of the *two-tube system* is that ripple currents tend to cancel out. This is, however, largely illusory. The quality of the radiation emitted by the x-ray tube fluctuates with time at some harmonic of the mains frequency The patient's body and other substances selectively absorb the radiation of lower energy more than that of higher energy Consequently, the waveshape of the ripple at the two cells is different and accordingly will not cancel completely. The selective absorption also means that the two-cell system cannot compensate completely for shift in the high-voltage supply to the x-ray tube. This is generally not a problem because the absorption coefficient for human tissue does not vary rapidly in the normal EKy range, which is 70 to 80 kv

The authors have built a *differential, direct-coupled electrokymograph* which has a bandwidth at the half-power point of 31 cps and a constant time delay of 0.0115 sec throughout this range.

One of the basic difficulties in taking *border tracings* is that the heart is not infinitely dense compared with the region just adjacent to the heart. Thus, one does not deal with an opaque shutter moving across a narrow window, but rather with the case of a nonuniform, semitransparent shutter. Thus, it is not possible to determine the exact position of the heart border except in its two extreme positions. These two positions could be determined as follows.

Suppose that one has a narrow slot of length S which admits x-rays to the phototube. The phototube is arranged on a lateral transport mechanism which is calibrated in terms of centimeters of lateral motion. Suppose one starts taking records with the slot over the lung field and moves the slot inward until fluctuations due to heart border motion just begin. This position is noted. Then the slot is moved inward until a position is reached where the fluctuations due to heart border motion just cease The peak-to-peak motion of the heart shadow is then equal to the difference between the two readings minus the slot length S. The position of the heart border at the two extremes may be found by the application of geometry. All points in between must remain in error to some extent.

The differential, direct-coupled electrokymograph enables one to obtain density recordings which can be calibrated against masonite standards with ease However, the fact that the heart shifts in position during its cycle renders the interpretation of density records somewhat difficult.

ELECTROKYMOGRAPHY: PRACTICAL APPLICATIONS

When one records an electrokymogram, the polarity of the apparatus is so arranged that *an increase of light causes a downward movement of the tracing*. Therefore, such a drop in the curve indicates either an *inward motion of the cardiac border (border tracing)*, or a *decrease in the thickness of the structure (densogram)*. The former may be due to contraction of a chamber, displacement by rotation or pull, or both.

Any wave occurring before the first large vibration of the 1st sound is *presystolic;* any wave occurring after the last vibration of the 2d sound is *diastolic* Any wave taking place between the begining of the 1st and the end of the 2d sound is *systolic*. If the galvanometer has a deflection speed of 0 01 sec, the effective speed due to the tailing off of the filter, when this is tuned to 120 cps, is approximately 0.02 sec. Timing of the waves could be obtained by a simultaneous recording of the ECG However, this tracing supplies scanty information about most mechanical events Henny, Boone, and Chamberlain used a carotid trac-

ing The authors prefer a phonocardiogram because this tracing supplies the most detailed information, while the carotid tracing is strictly connected, in most cases, to left ventricle dynamics and fails to supply information during diastole. If one has a multiple-channel recorder available, then EKy and phonocardiogram should be recorded, plus a carotid tracing or an ECG. The carotid tracing should be recorded through a piezoelectric microphone, which avoids mechanical delay.

If an ECG is to be taken simultaneously with the EKy, special attenuators must be interposed between the subject and the electrocardiograph Otherwise, the unshielded patient picks up electrostatic radiations from the high-tension components of the x-ray machine and there will be artifacts in the electrocardiogram. The graduated potentials applied to the nine dynodes of the phototube are obtained from the a-c power line. The fluctuations of the commercial power lines must be regulated or smoothed out before reaching the phototube

The phonocardiogram is recorded best by a tiny, flat, microphone fastened to the skin, near the apex, by tape.

Calibration. Calibration of electrokymograms is important. Comparison of tracings recorded over different structures, or over the same structure at different times, may be made only through use of calibrating devices. These indicate whether or not the change in amplitude of a wave corresponds to the different amplitude of a border motion. Various devices for calibrating have been built One of them calibrates density changes, another, amplitude of border motions However, any tracing of border motions also contains a component of density change acting on that part of the slit which is within the shadow. This cannot be excluded and separately evaluated Therefore, it is the opinion of the authors that, at present, one single device, modifying the intensity of the x-ray beam received by the fluoroscope and calibrating the sensitivity of the instrument, is the only one having practical utility.

A good *analysis of the waves* can be made only if the film moves at speeds of 50 to 100 mm/sec If, on the other hand, one is interested in the *magnitude of the waves*, film speeds of 10 to 25 mm/sec should be used

The pickup device is attached to the fluoroscopic screen by means of a brace It is centered so that it is fully exposed to the x-ray beam with the diaphragm narrowed down to a small field It can be fastened to a special screen according to the description of Grossman and Tiger

The procedure is performed by a two-man team The recording apparatus, the electrical unit, and the pickup device are assembled and the wire connection is attached. The patient is seated on a rotating stool in front of the fluoroscope and the microphone is fastened to the skin. A device for recording carotid tracings is placed around the neck. Carotid and sound tracings are checked and the patient is instructed on how to hold his breath. The room is darkened for fluoroscopy, with screened lights illuminating the panels of the instruments.

With the patient in the PA position, the pickup is placed under fluoroscopic control *at the cardiac apex*, with the slit perpendicular to and crossing that part of the silhouette to be studied. With the slit in place and the fluoroscope in operation, the operator regulates the amplitude of the deflections, asks the patient to hold his breath and starts the camera, keeping the light beam under observation. After obtaining a tracing of several heart cycles, the operation is interrupted, the pickup is moved to the next place, and the procedure is repeated. The position of the patient and that of the pickup, as well as the degree of amplification used, are recorded in the protocol for every tracing.

Ordinary technique for chest fluoroscopy is used, with 3 to 5 ma and 65 to 70 kv. Initial fluoroscopy with the open shutters takes only a few seconds, then the shutters are narrowed to a small opening. As actual total recording requires from 3 to 5 min, exposure to x-ray radiation is moderate

In general, the tracing should be recorded during voluntary apnea in an intermediate phase, because it has been shown that the pulsations of the lungs (and to a lesser extent, those of the hilar shadows and the pulmonary artery) are greater in inspiration than in expiration. Usually, after a few words of instruction, patients learn to hold their breath in an intermediate phase It is difficult, however, to obtain reliable tracings in children, patients in heart failure, and patients with chronic lung diseases, who are unable to control their respiration because of age or dyspnea. This difficulty can be overcome by using a *high-pass filter*, made of several condensers, interposed between the electrokymograph and the galvanometer This filter modifies the time constant, so that the tracing does not wander off the paper A slight error, proportional to the amount of reduction and consisting of a slight change in phase and configuration of the waves, is the result. Therefore, such a filter should not be used in cases where plateau-like waves are suspected because such waves are basically altered by the device

Positions of the Slit. Several standard positions for the slit can be used with the patient in either the sitting or the recumbent position (Fig 4-126)

1 *Patient in the PA position* apex, mid-left ventricle, and high left ventricle, pulmonary knob,

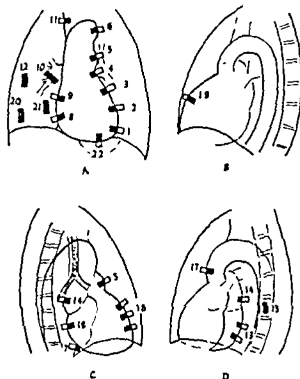


Fig. 4-126. Standard positions of the slit for recording electrokymograms Positions for border tracings are marked with black and white rectangles; positions for densograms are marked with black rectangles. A. Posteroanterior projection: 1, apex; 2, 3, higher positions on left ventricle; 4, left auricular appendage; 5, pulmonary arch; 6, aortic arch; 8, 9, right atrium; 10, right hilus; 11, superior vena cava; 12 and 20, right lung; 21, pulmonary veins; 22, left ventricle (inferior aspect). B. Left lateral: 19, right ventricle. C Right anterior oblique: 5, pulmonary arch; 7, inferior vena cava; 14, left atrium; 16, left ventricle (anterior aspect); 18, right atrium. D. Left anterior oblique· 13, left ventricle (posterior aspect); 14, left atrium; 15, descending aorta; 17, ascending aorta

aortic knob, high and low right atrium, pulmonary veins (densogram), right and left hilar shadows (densograms), high, middle, and low portions in both the right and left lung fields (densograms).

2. *Patient in 10° left and right obliques* left atrial appendage, ascending aorta.

3. *Patient in 45 to 60° left obliques* left atrium, descending aorta (densogram), high, middle, and low *posterior* ventricular border (left ventricle).

4 *Patient in 45° right oblique* left atrium, superior vena cava, inferior vena cava (deep inspiration); upper border of diaphragm (hepatic tracing); high, middle, and low *anterior* ventricular border (left ventricle).

5. *Lateral positions (left lateral preferred)* anterior slit, ventricular border, posterior slit, left atrial border

As a routine, with the patient in the PA position, one starts on the left side, first plotting *the apex* of the heart, then one or more tracings on *the upper part of the left ventricle.* This study is followed by that of the appendage of the left atrium, often visualized by a 10 to 15° left or right rotation. Next, the *aortic knob*, corresponding to the distal position of the aortic arch, is easily studied. The *descending aorta* can be studied in the left oblique position by placing the slit vertically against the spine or between this structure and the heart.

On the right side, one usually traces *the right atrium* at its most prominent point; occasionally, also at a lower point of its contour. The *ascending aorta* can be studied in normal subjects by using a 10° left oblique position. Its study in the posteroanterior position is possible only in mature or old individuals, if atherosclerosis and dilatation of the vessels are present.

It is not always possible to obtain a satisfactory tracing of the *superior vena cava.* In addition to large deflections, similar to those of the jugular phlebogram, there are often additional vibrations due to transmitted movements. On the other hand, it is easier to obtain good tracings of the *inferior vena cava* either in the posteroanterior or in the right oblique position. The patient should hold his breath in deep inspiration for this procedure.

For the plotting of the *hilar pulsations,* one should prefer the right hilar shadow as the one more clearly exposed. The slit is placed vertically across the hilar vessels as far away from the cardiac shadow as possible

For the recording of the *peripheral pulmonary pulsations, the slit is placed vertically, over* either the upper or the lower field of the lung: this tracing is a densogram.

The Left Atrium. One should use a series of tracings on account of the importance that changes of the waves may assume in mitral valve lesions (Haring et al., 1956)· (1) a border tracing of the left atrial appendage, (2) two border tracings in the left oblique position (high and low), (3) two border tracings in the right oblique position (high and low), (4) two border tracings in left lateral (high and low), (5) two densograms in left lateral Comparison of these nine tracings easily reveals possible artifacts (see also Fleischner et al, 1955) and shows the typical pattern.

The pulsation of the *right ventricle* is best picked up in the straight lateral view just above the point where it separates from the anterior chest wall. The best tracings are obtained with the subject in the recumbent position, however, patients with right ventricular hypertrophy also yield good tracings in the sitting position. Actually, the tracing of the right ventricle is often a densogram of this chamber

The *pulmonary veins* can be studied with the

slit placed vertically about 2 cm beyond the convexity of the right atrium in the posteroanterior position, as shown by Marchal. The veins composition, as shown by Marchal. The veins compose the middle and lower lobes of the right [illegible]

followed: the slit is placed vertically upon the border of the right atrium, then, in successive steps, it is moved laterally across the bright cardiohilar interspace, the final tracing is taken upon the hilus. Comparison of the tracings with those of the left atrium reveals that the *positive* presystolic wave recorded over the venous field corresponds to the *negative* presystolic wave present in the left atrial tracing (Fig. 4-131).

In the study of the various cardiovascular structures, the following data should be considered

1. *Amplitude of pulsation.* This can be evaluated by comparing the amplitude of pulsation of one structure with that of another, if they are recorded with the same degree of amplification (Fig 4-128A–D) Calibration helps in the comparison.

2 *Shape and time of the various waves* These can be evaluated by the use of optimum amplification and by timing the waves of the EKy with those of other records.

3. *Abnormal movements.* Transmitted and inherent pulsations can be differentiated by comparing a border tracing with a densogram of the same origin or those of two opposite borders.

4. *Dissociation between chambers* (dissociation between the atria, bundle branch block, AV block). This study is best accomplished by simultaneously recording the pulsations of two chambers (two electrokymograms)

5 *Cardiac output* Clinical determination of cardiac output has been attempted by means of electrokymography. The method, advocated by Ring et al, was based upon tracings of density changes of the ventricular mass (ventricular densograms) Calibration of the device was necessary. It is the impression of the authors that this method is not suitable for general use and also is probably not sufficiently accurate.

ANALYSIS OF NORMAL TRACINGS

It should be kept in mind that the electrokymogram (EKy) permits the study of entirely different structures, atrial, ventricular, arterial, and venous. According to the structure and its function, the tracing should be compared with a physiological or clinical tracing of atrial or ventricular contraction or of arterial or venous pulsation, recorded by other means

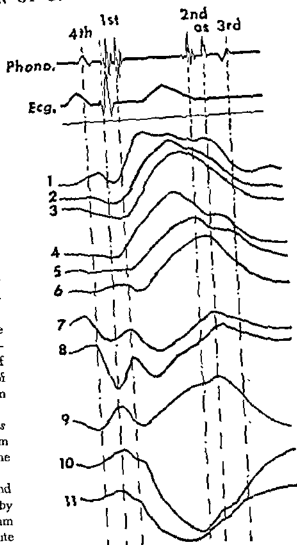


Fig 4-127. Comparison of various schematic electrokymograms with the phonocardiogram (*Phono*) and the electrocardiogram (*Ecg*). Electrokymograms 1, ascending aorta, 2, aortic arch, 3, descending aorta; 4, pulmonary artery; 5, hilus, 6, lung; 7, right atrium, 8, left atrium; 9, pulmonary veins, 10, left ventricle, 11, right ventricle

The EKy tracings represent the summation of *volume changes* of a chamber or vessel, *motions* due to rotation or total shift of the heart, and *tractions* from other structures. In particular, each atrium shows the effect of traction by its respective ventricle The visible changes in

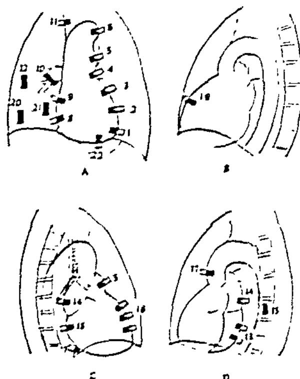


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slit placed vertically about 2 cm beyond the convexity of the right atrium in the posteroanterior position, as shown by Marchal. The veins coming from the middle and lower lobes of the right lung cross the descending arteries perpendicularly and stand out within the bright band of the lower bronchus. In order to identify this venous pattern with certainty, the following procedure should be followed: the slit is placed vertically upon the border of the right atrium, then, in successive steps, it is moved laterally across the bright cardiohilar interspace; the final tracing is taken upon the hilus. Comparison of the tracings with those of the left atrium reveals that the *positive* presystolic wave recorded over the venous field corresponds to the *negative* presystolic wave present in the left atrial tracing (Fig. 4-131).

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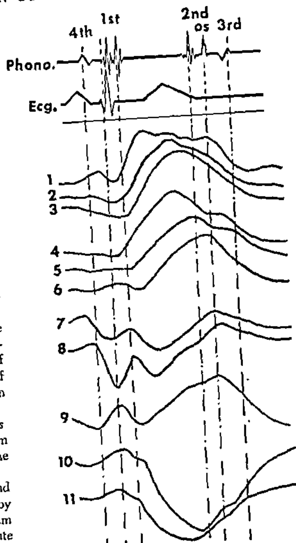


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The EKy tracings represent the summation of *volume changes* of a chamber or vessel, *motions* due to rotation or total shift of the heart, and *tractions* from other structures In particular, each atrium shows the effect of traction by its respective ventricle The visible changes in

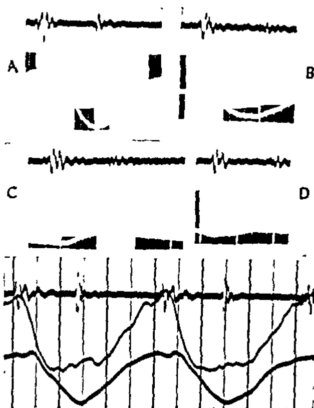


Fig. 4-128. Comparison of four tracings recorded on the same individual with the same amplification: A. Apex. B. High left ventricle. C. Aortic arch. D. Pulmonic arch. The phonocardiogram in (A) appears somewhat different in configuration, although taken on the same subject. This is due to relocation of the microphone for optimum visualization of the heart (Bottom) Simultaneous electrokymograms of the left ventricle. Upper tracing, phonocardiogram. Middle tracing, EKy of the apex Lower tracing, EKy of the left ventricular margin at medium level There seems to be precession of the apex due to its rotation during the tension period.

volume are greatest in the left ventricle and frequently decrease in the following order. (1) left ventricle, with highest amplitude at the apex, (2) right ventricle, (3) aorta, (4) pulmonary artery, (5) atria; (6) venae cavae and hilar shadows, and (7) lungs (Fig 4-128).

Left Ventricle. APEX. (Figs. 4-127 and 128) Usually, a small positive wave can be recorded immediately before or during the first group of vibrations of the 1st sound This is due to *left atrial contraction* which pushes a certain amount of blood into the left ventricle causing dilatation of the latter. This wave is absent in patients with atrial fibrillation, it is large in patients with left ventricular strain and higher left atrial pressure. The *tension period* is accompanied, first by a small depression, probably due to torsion of the heart, then by a slight rise.

The *main ventricular wave* consists of a large downward deflection which starts at the time of that large vibration of the 1st sound which is due to opening of the aortic valve. The descending branch of this wave reaches its lowest point at a time which varies in different subjects and with various positions, on account of variable modifications caused by rotation and displacement of the apex. In most cases, this point coincides with that large vibration of the 2d sound which is due to closure of the aortic valve. This coincidence, most commonly seen with the subject in sitting position, proves that the record is largely a volume tracing. In certain subjects, however, and particularly in the supine position, the maximum drop takes place at about two-thirds of systole and is followed by a shallow curve or a gently ascending slope (Fig 4-128, Bottom). Theoretically, the lowest point should precede the 2d sound by 0.02 sec (protodiastole).

Early diastole is marked by a small rebound and a rapidly ascending slope which ends at the time of the 3d heart sound (phase of rapid filling), then by a more gradual slope, or a horizontal line, which continues until the beginning of the following cycle.

CONVEXITY OF THE LEFT VENTRICLE. The waves reproduce volume changes of the ventricle more faithfully and denote to a lesser degree the effect of motion. The coincidence between lowest point of the main wave and 2d sound is seen more regularly. The drop of the curve is preceded by a slight rise during the tension period This may be actually due to a slight dilatation (Rushmer).

Tracings recorded *above* the apex usually seem to start later than those *at the apex* (Fig. 4-128, Bottom) This is due to less marked interference of motion phenomena in higher tracings and gives the impression that the contraction starts at the apex and spreads toward the base. This different timing of the waves gave rise to the erroneous concept of "ventricular peristalsis" when observed by roentgen kymography.

OTHER POINTS ON THE VENTRICULAR SURFACE. The left ventricle can be studied in various projections, such as the *left anterior oblique* (posterior aspect) and the *right anterior oblique* (anterolateral aspect). Tracings re-

corded in these positions present the same type of waves as the left margin in the PA position, except that they are smaller; *the lowest part of the main wave is frequently made of a shallow curve.*

The *densogram* of the left portion of the ventricular mass *resembles an apical tracing.* However, the ascending limb of the curve (diastole) is slower and reproduces less accurately the events of the cardiac cycle

The *isometric relaxation period* lies between the lowest point of the ventricular wave (if this coincides with the 2d sound) and the beginning of the rebound in early diastole (Luisada et al., 1948), not between that point and the peak of the rebound, as stated by others. The duration of this period was found to range between 0.04 and 0 07 sec by the authors, 0 07 to 0 14 sec by Mednick et al and 0 02 to 0 14 sec by Salans et al.

Right Ventricle. Indirect evidence of right ventricular activity may be found in tracings of the right atrium in the PA view, however, the data cannot be considered accurate because of the influence from *venous return* The best tracings are recorded in the *lateral* views with the slit placed where the *cardiac shadow separates* from that of the anterior chest wall, or just below this spot (*Fleischner*) The tracing of the right ventricle is largely a densogram It presents a small positive wave at the beginning of the 1st sound and otherwise shows a *curve similar to that of the left ventricle.* The absolute amplitude of the right ventricular tracing is far less than that of the left but this may not be noted on account of higher amplification, except in comparative studies.

Simultaneous tracings of the two ventricles can be taken with the subject in a lateral position and two pickup units, one having the slit across the anterior border (right ventricle); the other, across the posterior border (left ventricle).

Left Atrium. The typical tracing (Fig 4-129D) shows a rapid downward wave in *presystole* starting about 0.14 sec before the 1st sound. If the heart rate is rapid, there may be only one slow wave in diastole with a peak at the end of left atrial contraction. *This peak* coincides with the first vibration of the 1st sound or takes place slightly before it. *If a 4th* (atrial) sound is *present*, it occurs *during* the downward branch of the atrial wave. The presystolic wave is *deeper in patients with left* atrial hypertrophy and disappears in patients with atrial fibrillation. *After this wave, the tracing* rises sharply to a small positive notch (AV *notch*) *during the first part of the 1st sound.* After this, two negative waves are present, one *in systole* and the other in *diastole*. The *systolic collapse* of the left atrium is related to the dynamics of the left ventricle left ventricular

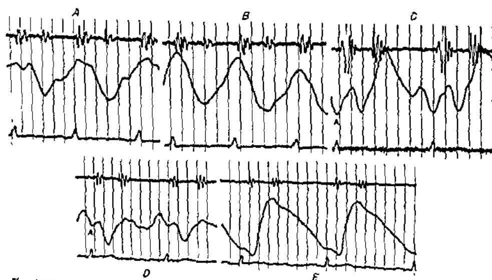


Fig. 4-129. Electrokymographic tracings A Apex B Upper part of left ventricle. C Right atrium. D. *Left atrium* E. Aortic arch. *A wave* is presystolic atrial contraction. *Phonocardiogram (above)* and *ECG (below) are used for timing.*

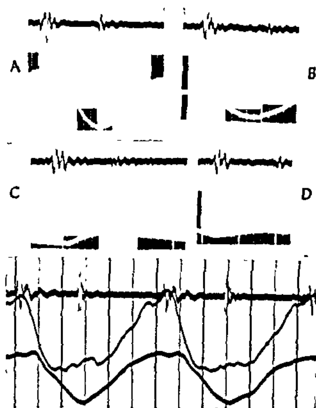


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OTHER POINTS ON THE VENTRICULAR SURFACE The left ventricle can be studied in various projections, such as the *left anterior oblique* (posterior aspect) and the *right anterior oblique* (anterolateral aspect). Tracings re-

presents marked individual variations, but resembles, in general, a carotid tracing. It has (1) a small positive wave during the first part of the 1st sound, probably due to a rising of the aortic valve during isometric contraction; (2) a sharp rise after the second large vibration of the 2d sound (opening of the aortic valve), (3) an anacrotic depression in the first part of systole; (4) a peak during the last part of systole but well before the 2d sound, (5) an incisura or predicrotic notch, which may coincide with, or persist slightly beyond, the 2d sound, (6) a dicrotic wave, which usually is small and rounded; and (7) a few small aftervibrations.

A *densogram* of the aortic arch gives a similar tracing. However, it has been proved that the densogram and the border tracing are *not* identical. This is due to the fact that the border tracing has an important component derived from lateral motion of the aortic arch.

DESCENDING AORTA. Since the descending aorta does not present a sharp contour on fluoroscopy, only a *densogram* is possible in normal subjects. The tracing is similar to that of the aortic arch, but shows a slight delay in

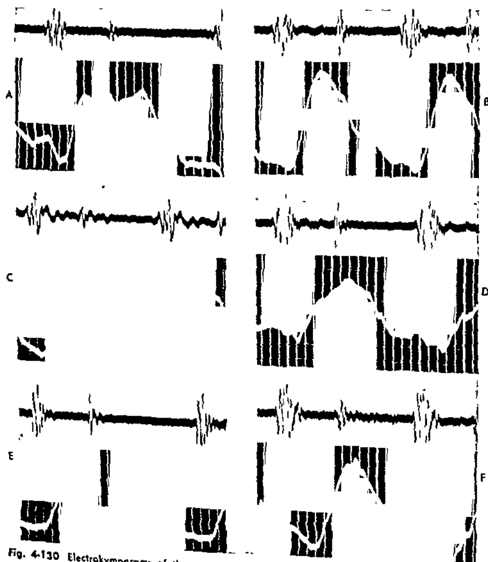


Fig. 4-130 Electrokymograms of the aorta. A. Ascending aorta. B. Aortic arch. C. Descending aorta (densogram). Electrokymograms of the pulmonary arterial wave. D. Pulmonary knob. E. Right hilus. F. Visible base of the right lung.

contraction lowers the AV septum and creates a suction within the atrial cavity, which is compensated only gradually by increased flow of blood. Therefore, an inward movement of the free atrial wall takes place. The highest level of the tracing is reached from 0.05 to 0.08 sec *after* the end of systole, when the mitral valve opens. After this positive notch (*V wave*), there is a *diastolic collapse*, which is probably due to passive flow of blood into the left ventricle after the opening of the mitral valve. The rise of the tracing at the end of ventricular systole is steeper with the patient in the supine position.

Densograms present a clear-cut presystolic downward wave but are not as informative as border tracings because of possible superimposed pulsations of the pulmonary veins and arteries. The tracing of the *left atrial appendage* is sometimes not accurate during ventricular systole if the pulmonary artery is dilated; the record taken in the left oblique position may not be accurate during ventricular systole if the descending aorta is enlarged; that recorded in the right oblique position is often the best.

Right Atrium. The tracing recorded over the margin of the right atrium is similar to that of the left, though smaller Contraction of the atrium during presystole is manifested by a very small, rounded, downward wave (Fig 4-129C). After this, the tracing either reaches the base line or rises above it, but drops again during ventricular systole The latter is manifested by a sharp downward wave (systolic collapse) which is usually deeper than the atrial wave. The subsequent course of the atrial tracing varies with the position of the subject. In the sitting position, the tracing rises slowly and attains its maximum height at the time of tricuspid tracing, in the recumbent position, the rise is quicker and there may be a convex line which brings the tracing above the base line. Another drop, however, takes place after the opening of the tricuspid valve (diastolic collapse).

The early-diastolic and the presystolic collapses are due to changes in volume of the atrium because of passive inflow into the right ventricle and because of right atrial contraction The systolic collapse is partly due to decreased atrial pressure (traction on the AV septum) and partly to total atrial displacement by the right ventricle.

The tracing of the right atrium has a superficial resemblance to that of the systemic veins However, the A wave is negative instead of positive and the junction between this wave and the systolic collapse occurs before the start of ejection. Therefore, the waves should be marked, as in the left atrium, as A, AV, and V. In cases with AV block, a "pure" atrial tracing is recorded. *Densograms* of the right atrium are not always clear, due to superimposition of the right atrial shadow over that of the right ventricle.

Studies of the time relationship between the contractions of the right and left atria can be made with the subject in the right oblique position. Two pickups are placed posteriorly, one above the other. The higher records the left atrial contraction; the lower, the right. With this method, the authors found a delay of 0.025 to 0.030 sec of the left over the right atrial contraction; this was confirmed by Mednick et al

Aorta. ASCENDING AORTA. The tracing of the ascending aorta presents a typical pattern, different from that recorded over the aortic arch. It has an *early-systolic* drop, a rapid rise, an early peak, a slight descent (or none at all) during the second half of systole, a small incisura, and a high, occasionally prolonged, wave after the incisura This tracing differs from the reconstruction of aortic pressures by Hamilton and Dow, indicating that the pattern recorded is not merely caused by volume changes (parallel to pressure changes), but is also markedly affected by motions of the heart and vessels. The lowering of the aortic root by ventricular systole and the medial displacement of the ascending aorta by rotation of the heart in the same phase apparently reduce the height of the aortic wave. This is confirmed by the initial drop of the tracing. Opposite movements, taking place in diastole, add their effect to that of the dicrotic wave and create a high wave on the tracing The proximity of the ascending aorta to the left ventricle may contribute to the fact that, in some subjects, the profile of the aortic pulse during systole greatly resembles a tracing of intraventricular pressure (Fig. 4-130A)

AORTIC ARCH The tracing of the aortic arch

tracing, may be present in the tracing of the lung. As both arterial and venous changes of the blood content of the lung are recorded, it is possible that some of the waves, as well as the peak, are influenced by the effect of left atrial and left ventricular contractions, transmitted through the veins.

The normal amplitude of the pulse of the lung is usually about one-half that of the hilus. However, there are individual variations: differences between lobes; influence of respiration (inspiration-greater waves, and vice versa), and other changes due to modification of intrathoracic pressure (Valsalva maneuver, etc.)

Velocity of the Arterial Waves in the Pulmonary Circulation. The velocity of the pulse waves in the lesser circulation can be studied by comparing the tracings obtained with the slit over the pulmonary knob, the right hilar shadow, and the visible base of the right lung, using as timer the main vibration of the 1st sound (Fig. 4-130)

The average times of arrival of the pulse waves in 10 normal subjects were found as follows 0 08 sec for the pulmonary knob, 0 12 sec for the right hilus, and 0 16 sec for the base of the right lung These data were obtained by measuring on the tracing the distance from the beginning of the 1st sound to the rise of the wave. Corrected figures are about 0 06 sec lower because the opening of the pulmonic valve takes place later than the beginning of the sound A pulse-wave velocity of 2 m/sec between pulmonary knob and right hilus, and 2.75 m/sec between right hilus and visible base of the right lung, was calculated

While the speed of the pulse in the lesser circulation is less than in the greater (grossly, one-third of the latter), the pulse increases its speed in the small, less extensible, arterioles both in the lesser and in the greater circulation

Venae Cavae. SUPERIOR VENA CAVA. A good tracing of this structure is seldom ...

... a record which resembles the jugular tracing and shows the three typical, positive waves (A), (C), and (V). Smaller vibrations are frequently superimposed

INFERIOR VENA CAVA This tracing is recorded with the subject holding his breath in deep inspiration. The best tracing is obtained with a slight rotation toward the right oblique

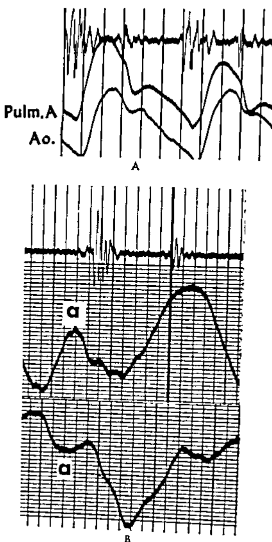


Fig 4-131. A Simultaneous electrokymograms (border tracings) of the pulmonic and aortic arches in the posteroanterior position showing a slight precession of the pulmonic (*Pulm A*) over the aortic (*Ao*) pulse B Electrokymogram of the pulmonary veins compared with that of the right atrium The former has a positive wave in presystole (a) while the latter has a negative presystolic wave (a) Superimposed tracings

There is a small, presystolic, positive wave, due to slower flow of blood at the time of atrial contraction (*A wave*). This is followed by a deep negative wave (*systolic collapse*). Then follows a slow rise, culminating in a single or double wave about 0 10 sec after the second sound (*V wave*) This is due to slow engorgement of the vein until the tricuspid valve opens. The subsequent drop reaches its maximum after the middle of diastole (diastolic

the rise of the pulse in comparison with the rise in the arch (Fig. 4-130C).

Pulmonary Artery. The tracing of the pulmonary arch is usually easily obtained. However, a large left hilar shadow or a dilated descending aorta may modify the tracing. The pulsations of the latter structures (recorded as densograms) are usually of a smaller amplitude and their influence is manifested mainly in a smoothing of the waves without other distortion The pulmonic pulsation starts with the opening of the pulmonic valve (second part of the 1st sound); then rises sharply, and occasionally shows a slight change of slope indicating an anacrotic depression. The peak is reached at about two-thirds of ventricular systole. The predicrotic notch is usually deep and occurs from 0.06 to 0.08 sec after the main vibration of the 2d sound. The dicrotic wave is usually well defined and is higher than that of the aorta. Its peak is usually 0 10 to 0 12 sec after the main vibration of the 2d sound Another positive wave may be seen in late diastole before atrial contraction (Fig. 4-130D).

A *densogram* of the pulmonary arch is easily recorded. The tracing is similar to the border tracing. It may be necessary to resort to this record whenever the contour of the pulmonary artery is obscured by hilar shadows or pulmonary consolidation.

In a comparative study of the aortic and pulmonic tracings by simultaneous records, the authors found a precession of 0 02 to 0 03 sec in the rise of the pulmonic pulse over that of the pulse of the aortic arch Mednick et al found a shorter interval (0 01 sec) However, individual and respiratory variations included from 0 03 sec precession to 0 02 sec delay As the progress of the pulses from the valves to the knobs varies according to elasticity of the walls and the pressure of the vessels, the variations found by Mednick et al and by Chamberlain et al may be due to these peripheral factors, in addition to changes in the timing of pulmonic and aortic opening caused by change of pressure

Hilar Shadows. The tracings of the hilar shadows are *densograms* and represent the variations of opacity of the hilar regions caused by changes in the blood content. The amplitude of the normal hilar pulsation is between one-half and two-thirds that of the pulmonary arch. Additional pulsatory phenomena transmitted from the heart and great vessels may influence the tracing without decreasing its value Following a small negative wave, *a large positive wave* occurs. This starts approximately 0 04 sec after the pulse of the pulmonary artery and 0.12 sec after the beginning of the 1st sound. The peak of the pulse wave is reached at or about the time of the main vibration of the 2d sound. It may be followed by a small notch and by a small dicrotic wave. The initial negative wave is synchronous with the peak of the carotid pulse. A second small negative wave is sometimes present in presystole (Fig. 4-130E).

The positive wave of the hilar pulse indicates the arrival of the arterial pulse in the branches of the pulmonary artery. However, the pulsations of the pulmonary veins also influence the tracing and the early-systolic depression may be due to acceleration of the venous flow.

Pulmonary Veins. Tracings recorded in the right intercardiohilar space, as suggested by Marchal, show close relationship to those of the atria. In the typical tracing, a presystolic positive wave (increased volume) can be noted (*A wave*); this is synchronous with the negative wave (contraction, decreased volume) of the left atrial tracing (Fig. 4-131B). Later on, a small positive notch (*AV wave*), a *systolic collapse*, a positive peak at the time of mitral valve opening (*V wave*), and a diastolic collapse, are present. In other words, the tracing is a typically "venous" tracing.

Lungs. Pulmonary tracings were extensively studied by Marchal (1946). The densogram of the lung is a tracing which resembles that of the hilus However, there are several differences.

1. There is a greater delay in the rise of the pulse wave, which takes place from 0 16 to 0 18 sec after the beginning of the 1st sound and about 0 04 sec after the rise of the hilar pulse.

2 There may be a greater delay of the peak, which occurs from 0 08 to 0 10 sec after the main vibration of the 2d sound.

3 The curve is often more rounded and exhibits no evidence of a dicrotic wave (Fig 4-130F)

Both the presystolic and the early-systolic downward waves, already noted in the hilar

direct recording of successive radiograms on films of standard dimensions while the second utilizes the cinematographic record of the fluorescent images. The direct method is commonly known as *rapid seriography*. The x-ray films, in rolls of 9.5 in. by 30 or 70 ft or cut in sheets of 12 by 10 in., are stored in special magazines. A motor-driven mechanism advances them between the intensifying screens, automatically activating the circuit of the rotating anode tube which exposes the film, and eventually stores them again. The most modern seriographic units take a series of 30 or 70 radiograms in one or two orthogonal projections, at a maximum frequency of 12 per second.

The direct method should be considered as a cineradiological method when the seriograms are reproduced on movie films, the projection of which can represent the dynamics of the organ under examination.

The cinefluorographic apparatus (Ramsey et al.) consists of a fluorescent screen, usually 14 by 14 in., with high luminescence and little lag, a movie camera, 16, 35, or 70 mm (Watson et al.), and a synchronous electric motor which drives it. The lens of the movie camera is very fast (f 0.71) and chromatically corrected for the yellow-green light emitted by the fluorescent screen. In order to reduce the radiation to the patient, special mechanical or electronic interrupters stop the emission of x-rays when the camera shutter is closed. The modern apparatus also has a device to synchronize the electrocardiographic tracings which have been recorded simultaneously with the cinefluorograms. The cinefluorographic examination is recorded on films which are ultrarapid and very sensitive to the yellow-green light, at a variable frequency of 7.5 to 120 frames per second, and for a comparable time of 25 and 3 sec respectively. The negatives are printed on 16-mm positive films since the smaller-sized projector is more convenient. Also, in this fashion, it is possible to store all the original negatives which otherwise would be deteriorated by projection (Fig. 4-134).

Recently, a new type of fluorescent screen, the *image-intensifying tube*, has been introduced. It permits increasing the frequency of the cinefluorographic exposures and reduces the factors of radiation exposure. Actually, there are on the market tubes of 5- and 11-in. diameter. In the latter, however, the intensification of the images is less than in the 5- and 9-in. tubes.

The pictures obtained by the cinefluorographic method, although sufficiently definite and detailed, appear enlarged and geometrically distorted because of the short distance between the target and the fluorescent screen (30 to 40 in.). The seriographic images do not show these artifacts, which are particularly evident in films taken by means of the *image-intensifying tube*.

From a practical point of view, rapid seriography and cinefluorography, even in their most modern technical realization, present a number of advantages and disadvantages. How-

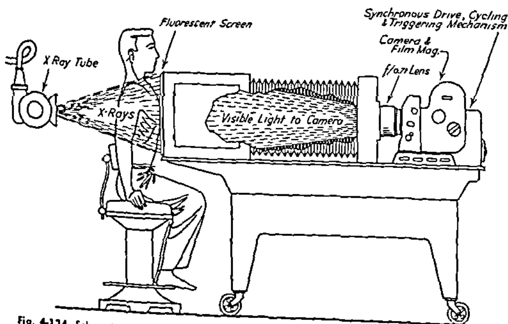


Fig. 4-134. Schematic representation of a modern cinefluorograph. (Courtesy of General Electric Co., X-ray Dept.)

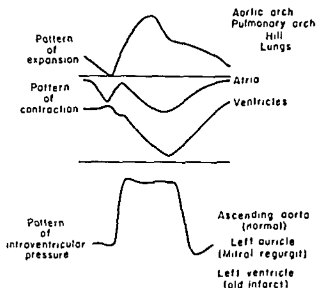


Fig. 4-132. General patterns (normal and abnormal) found in electrokymography.

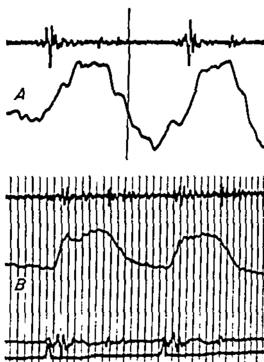


Fig. 4-133. A. Sound tracings and "plateau pattern" of left atrium in a patient with a mitral valve lesion. B. Pressure tracing of left atrium of same subject.

collapse). No *C* wave is present, but a small notch (*AV*) is sometimes visible.

The tracing of the inferior vena cava is similar to the hepatic tracing of normal subjects and is the result of the same physiological phenomena.

USES OF ELECTROKYMOGRAPHY

Electrokymography has been used in many fields

1 *Physiological applications.* Studies of the relationship between the events of the various cardiac chambers have been made by Chamberlain et al (1947), Luisada et al. (1948), Luisada and Fleischner (1949), Salans et al. (1950), and Mednick et al (1950) Ring et al (1949) tried to measure cardiac output by this method.

2. *Studies of bundle branch block* Following studies by Ellinger et al. (1948), Samet et al. (1950) made an exhaustive study of this condition

3. *Studies of patients with rheumatic lesions of the mitral valves.* Following a study by Luisada and Fleischner (1948) of left atrial tracings, a score of publications has appeared. They led to the description of a new pattern (*the plateau pattern*) in mitral regurgitation (Part 7, Chap 2). This was investigated before and after commissurotomy (Haring et al) and compared with left atrial pressure tracings (Luisada and Liu, 1958, Fig 4-133).

4 *Studies of patients with coronary artery disease* Luisada and Fleischner (1948) and Dack and Paley (1952) described basic abnormalities of the left ventricular pattern. They seem to have importance in the determination of the damage caused by myocardial infarcts (Part 10), even when no permanent aneurysm is visible.

Other clinical studies have been made on patients with arrhythmias, aortic insufficiency and stenosis, coarctation of the aorta, aortic aneurysms, pericarditis, etc.

CINERADIOLOGY

DEVELOPMENT AND METHODS

In 1897, two years after the discovery of roentgen rays and the practical demonstration of the first movie projector, McIntyre showed a brief cineradiographic sequence of the movement of a frog's leg. Thus, cineradiology was born. It developed slowly until about 1930 when the radiological equipment, the intensifying and fluorescent screens, the lenses, and the films had been considerably improved (Jarre, Reynolds, Janker)

As predicted by McIntyre, two methods developed: the *direct or cineradiographic* and the *indirect or cinefluorographic* Tl

change manifests itself In the LAO position, *for example, the right atrium* and ventricle are either partially or totally superimposed. In the presence of small right-to-left shunts, the inter*atrial shunt can be differentiated* from an interventricular shunt because the former occurs during atrial contraction and (to a lesser *extent) during the* "systolic collapse *of the* atrium," whereas the interventricular shunt [illegible]

abnormal pulmonary vessels; atrial septal de*fects with left-to-right shunt, or blood coming* from the inferior vena cava or the coronary sinus when it does not contain contrast me-

[illegible]

The electrocardiographic tracings, taken simultaneously with the cineangiocardiographic examination and synchronized with the frames, are at times very useful, especially when a *too-rapid injection* of the contrast medium produces *right atrial or ventricular premature contractions* or when myocardial hypoxia, due to the coronary *circulation of the contrast me*dium, has produced *a transient, complete AV block* If one considers that only from four to *six cardiac cycles are clearly legible in the* dextro- or levoangiocardiograms, it is understandable that the diagnostic value of the



Fig 4-135. Photographs from a 35-mm negative There are four phases of the *cardiac* cycle. Diagnosis, pulmonic stenosis. *(See text.)*

ever, considering the need for the radiological exploration of the cardiovascular system, the seriographic method, aside from the high operational expense, is to be preferred in the anatomoradiographic investigation, whereas the cinefluorographic method should be preferred for the study of cardiovascular dynamics.

INVESTIGATION OF THE CARDIOVASCULAR APPARATUS

The purpose of a cineradiologic examination of the cardiovascular apparatus is to study changes in cardiovascular dynamics. Many anatomical changes, congenital or acquired, cannot be diagnosed directly but their existence can be deduced from existing functional alterations.

The examination of the heart and great vessels is performed either with or without an opaque contrast medium. The examination of the other vessels, venous and arterial, must be made with a contrast medium since their radiographic density is the same as that of the surrounding tissues

The cinefluorographic study *without* contrast medium should be considered as the complement of cardiac fluoroscopy because it permits the documentation of the fluoroscopic observations. Furthermore, the evolution of any change can be followed The cinefluorographic procedure, particularly that utilizing the image-intensification tubes, requires a short time compared to that for the common fluoroscopic examination. In the hazy light of the fluoroscope, the dynamic changes of the cardiovascular profile are not always visible in obese subjects, or in patients with thick chests or tachycardia, but these changes rarely escape the cinefluorographic examination when the recording speed is about 13 frames per cardiac cycle. In fact, the black-and-white images projected on the movie screen are perceived by the human eye much more easily than those visible on the fluorescent screen The new analytical projectors also allow one to see the action in slow motion or in single frame, thus making it possible to recognize the anatomical structures and their movements, even when they are superimposed. The altered dynamic behavior in small areas of infarction of the ventricular wall, in areas of adhesive pericarditis, in small aneurysms, or in the left atrial walls in mitral stenosis, and so on, can be studied and diagnosed on the basis of a well-conducted cinefluorographic examination.

The methods of cinefluorographic exploration of the cardiovascular system *by means of contrast media* are: venous and arterial angiography, angiocardiography, and cardiography. The preparation of the patient, the selection of the contrast medium and of the radiological position do not differ from the conventional radiographic techniques. The measurement of circulation time is obviously not necessary.

Cineangiocardiography is recorded by a cinefluorographic unit with a 14 by 14-in. screen at 15, 30, or 60 frames per second. The thickness of the thorax, the cardiac volume, the heart rate, the age of the patient, and the radiological position are the factors which determine the choice of camera speed The objective is that of obtaining the maximum number of good frames *per cardiac cycle* and not per second. The purpose is to record on the cineangiocardiogram all the events of the mechanical cardiac cycle (Fig. 4-135).

Since during each phase of the cycle different anatomical structures act actively and passively, their form and function can be evaluated only in some phases of the cycle and not in others. Often the diagnosis depends on a few frames which unequivocally document the cardiovascular lesions For example, in regard to pulmonary valvular stenosis, it is known that it is difficult to differentiate complicating infundibular hypertrophy from a concomitant infundibular stenosis (tunnel type). It has been observed (Campeti) that the infundibulum of the pulmonary artery, normal or pathological, reaches its maximum degree of distention during the isometric contraction and the first part of the rapid ejection (Fig. 4-136). The author believes that *only in this brief part of the cycle* (0.06 to 0 15 sec, or between 1 and 3 frames) is it possible to make a differential diagnosis based upon the recognition of the morphological changes and the appreciation of the degree of distensibility of the walls of the infundibulum.

For the diagnosis of the hemodynamic alterations produced by anomalous vessels, septal defects, valvular insufficiency, etc, the anatomical-topographic criteria are not sufficient, especially when the cardiac chambers and the large vessels are overlapping. It is then that one has to consider the phase of the mechanical cardiac cycle in which the hemodynamic

change manifests itself. In the LAO position, for example, the right atrium and ventricle are either partially or totally superimposed. In the presence of small right-to-left shunts, the interatrial shunt can be differentiated from an interventricular shunt because the former occurs during atrial contraction and (to a lesser extent) during the "systolic collapse of the atrium," whereas the interventricular shunt manifests itself during late systole. The filling defects of the right atrium (due to: contraction of the hypertrophied myocardial bands, abnormal pulmonary vessels, atrial septal defects with left-to-right shunt, or blood coming from the inferior vena cava or the coronary sinus when it does not contain contrast medium) cannot be differentiated by anatomical-topographic criteria and require a chronological study for evaluation.

The electrocardiographic tracings, taken simultaneously with the cineangiocardiographic examination and synchronized with the frames, are at times very useful, especially when a too-rapid injection of the contrast medium produces *right atrial or ventricular premature contractions* or when myocardial hypoxia, due to the coronary circulation of the contrast medium, has produced a *transient, complete AV block* If one considers that only from four to six cardiac cycles are clearly legible in the dextro- or levoangiocardiograms, it is understandable that the diagnostic value of the

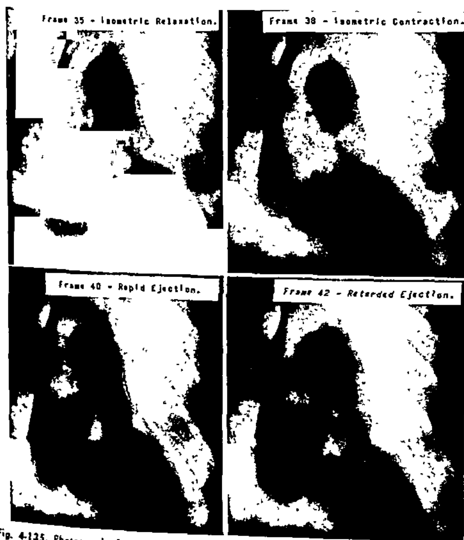


Fig. 4-135. Photographs from a 35-mm negative There are four phases of the cardiac cycle. Diagnosis, pulmonic stenosis. (See text.)

examination may be minimized by premature beats or conduction disturbances. However, it is almost always possible to recognize in the cineangiocardiograms the mechanical and hemodynamic changes caused by these disturbances, even without reference to an ECG.

In view of the above, the author believes that the angiocardiographic examination by the direct method, although it has the advantage of photographically perfect radiograms, does not absolutely allow the representation of the mechanical cardiac cycle in all of its phases Certainly, six or ten roentgenograms *per second* are not sufficient to study an infantile or *rapid heart, the cycle of which only lasts from* 0 30 *to* 0.50 sec.

A *special field* of application of cinefluorography with the 5-in. image-intensifying tube has been recently demonstrated in *selective angiocardiography* (Sones) which consists of the angiographic study of individual sections of the cardiac system. Usually, this is done in the course of cardiac catheterization, placing the tip of the catheter in the proper position and rapidly injecting small amounts of contrast medium. The examination can be repeated three times in the same sitting, depending on the condition of the patient, as long as the contrast medium is eliminated by the kidneys. The operator follows catheterization by means of a small televisor connected to the fluoroscopic tube When he desires to record the action by cinefluorography, with or without the injection of contrast medium, the movie camera is con-



Fig. 4-136. Photographs from a 35-mm negative. Four phases of the cardiac cycle in LAO. Diagnosis, pulmonic stenosis. (See text.)

nected to the fluoroscopic tube by moving a small lever. The small available surface of the tube (diameter 4.5 in.) limits the application of this technique primarily to pediatric cardiology.

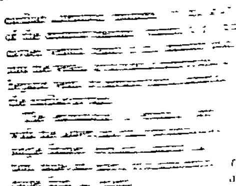
The other angiographic examinations (cerebral, pulmonary, etc., venous or arterial angiography) recorded by cinefluorography, have not demonstrated any particular advantage *over those made* with the conventional techniques.

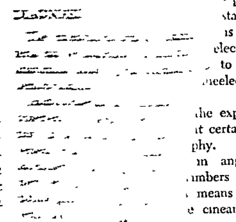
INTERPRETATION

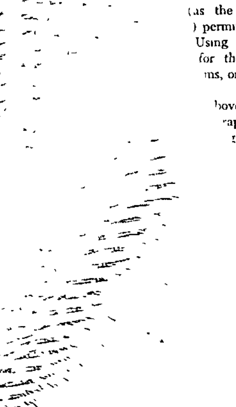
The 16-, 35-, and 70-mm films can be read directly on the viewing box by the use of magnifying lenses, or on the movie screen by still frame projection. The interpretation, however, is difficult and requires that the observer use considerable imagination in order to correlate the iconography of the static images with the cardiovascular mechanics. The use of movie projectors has solved the problem of interpretation only partially. In fact, the projection at normal speed (16 frames/sec) does not permit one to follow the rapid events of the cardiac cycle.

The best method is that of reproducing the negatives from 35- and 70-mm film on [illegible] positive films. Each film sequence, which is generally from 60 to 100 in. in length, is [illegible] each end and made into the form of a loop [illegible] allow continuous projection. The 16-mm [illegible] used by the author was that constructed by [illegible] berg and Watson. It permits controlled variation of the speed of projection between 16 and 6 frames/sec without flicker, and projection of a single frame, forward and backward. The projector [illegible] remote control, so that the observer can [illegible] the screen and observe at will the static [illegible] namic aspects of the film. Normally, the [illegible] projected at a convenient speed a [illegible] times, so that one can form a general [illegible] the examination and recognize possible [illegible] in angiocardiographic and cinefluoro[illegible] niques. In this fashion, one attempts [illegible] visualize the cardiovascular structures [illegible] thology, their dimensions, and the [illegible] relationships. The observation is [illegible] tended to their mechanics, to the [illegible] the events and finally to the [illegible] lowing progressively the pas[illegible] medium in the cardiac cham[illegible] vessels from the venae cavae [illegible]

During this prelimin[illegible] tion, it is possible to [illegible]


tive the [illegible]tson. [illegible]d by [illegible]oelec- [illegible]such a [illegible]e light [illegible]nection [illegible]ocardio- [illegible] *registra-* [illegible]nographic [illegible] projection [illegible]stant of the


[illegible]is similarly [illegible] electrocardio- [illegible] to correlate [illegible]neelectrokymo- [illegible] the experimental [illegible]t certain advan- [illegible]phy. [illegible]in angiographic [illegible]mbers and large [illegible] means of a den- [illegible]e cineangiocardio- [illegible] measurements re- [illegible](as the ordinate) [illegible]) permits the trac- [illegible] Using techniques [illegible] for the registra- [illegible]ms, one can also


[illegible]bove-described [illegible]raphic repre- [illegible]tram in its [illegible]rances [illegible] chnique [illegible] of the [illegible] of the [illegible]e to [illegible]lter- [illegible]eas [illegible]rly [illegible] come

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Fig. 4-136. Photographs from a 35-mm negative. Four phases of the cardiac cycle in LAO. Diagnosis, pulmonic stenosis. (See text.)

Cineangiocardiometry. This is a graphic and chronological plotting of variations in size of the areas and diameters of the cavities and large cardiac vessels. By means of single-frame projection, the contours of cavities and great vessels, outlined by contrast medium, are traced on separate sheets of paper and progressively numbered The anatomical points of reference are countersigned. The beginning and the end of the primary phases of the mechanical cardiac cycle are marked at the bottom of every sheet. The surface areas of the silhouettes of the cardiac chambers are then measured with a planimeter.

The most representative diameters of the chambers and vessels are first traced on the basis of the anatomical points of reference previously marked, afterwards, they are measured and the measurements are then chronologically noted These measurements, however, cannot be directly reported on the graph paper because they contain an error caused by the geometric distortion and the above-mentioned enlargement of the cinefluorographic image. In order to keep the error within acceptable limits, each single measurement is recorded as a percentage of the arithmetic mean of the entire series of measurements The data can thus be transposed to graph paper on the ordinate and correlated with the time, traced as the abscissa By joining these points, one obtains curves not too dissimilar from the electrokymographic curves The time is calculated on the basis of the number of frames/sec, since the camera is synchronously driven, and periodically controlled by oscilloscopic examination

The curves express, as a function of time, the variation of the diameters and of the areas from their *ideal* static dimensions, which on the curves are represented as values of 100 per cent These curves also express the movement, independently of the dimensions of the examined structures Cineangiocardiometric tracings of different structures can be correlated among themselves and with the densitometric and electrocardiographic tracings

Cineelectrokymography. This is the electrokymographic registration of the movements of the cardiovascular structures directly on the movie screen The cinefluorographic examination, with or without contrast medium, is made at 30 or 60 frames/sec with a 35-mm camera, and synchronized with an electrocardiographic tracing. The negatives are printed on positive 16-mm film and projected by means of the analytical projector of Weinberg and Watson. The cardiovascular movement is registered by means of an electrokymograph, the photoelectric cell of which has been adapted in such a way as to react to the variations in the light emitted by the projector. A special connection between a *remote marker* of the electrocardiograph and the projector provides for registration at the base of the cineelectrokymographic tracing at the instant in which the projection of each frame occurs. Since the instant of the recording of every single frame is similarly marked at the base of every electrocardiographic tracing, it is possible to correlate the electrocardiographic and cineelectrokymographic tracings

The method is as yet in the experimental phase, but it seems to present certain advantages over roentgen kymography.

Densitometry. Variation in angiographic densities of the cardiac chambers and large vessels can be measured by means of a densitometer by projecting the cineangiocardiogram in single frames. The measurements recorded on graph paper (as the ordinate) against time (as the abscissa) permits the tracing of continuous curves Using techniques similar to those described for the registration of the cineelectrokymograms, one can also record the *cinedensograms*

The correlation between the above-described tracings, therefore, permits a graphic representation of the cineangiocardiogram in its mechanical and hemodynamic appearances

CONCLUSION

High-speed cinefluorography is a technique which enhances the investigative studies of the *function* of the various organ systems of the body Conventional radiology enables one to diagnose the disease when the anatomical alterations have already been produced, whereas cinefluorography may reveal them at an early stage of functional alteration

The advent of cinefluorography has created within the specialty field the need for a specialized radiologist, *the cineradiologist*. This is a physician with a solid background in physiopathology and special training in radiology.

It is a general feeling that cinefluorography will become a routine procedure when the new

its shape, whereas, *during atrial contraction*, it changes size and shape, and the images of the auricular appendage and of the sinus finally disappear. In fact, in the first two phases, *rapid filling* and *diastasis*, there are only pressure and elastic factors operating to produce the recoil while, in the third phase, that of true atrial systole, those of myocardial activity appear to produce the contraction.

Very often, in the oblique views, it is possible to recognize the isometric contraction, in that the right outflow tract is distended and the apex of the ventricle is slightly retracted while the pulmonary artery is still at its minimum diastolic diameter and the contrast medium is contained by the still closed semilunar valves The ejection is characterized by the passage of the contrast medium into the pulmonary artery, which increases in diameter and density, and also by the retraction of the ventricle. At the end of ejection, the distended sinuses of Valsalva projects over the underlying contracted pulmonary infundibulum

The *signs of altered cardiac mechanics* must be analyzed by alternating slow and single-frame projection. *The movements of the walls of the cardiac chambers may be distinguished as active and passive The active movements* are due to myocardial contraction of the cavity, whereas *the passive* ones are the result of the contraction of cavities upstream or downstream in the case of valvular insufficiency

Simple inspection does not always make it possible to correlate the various chamber movements. It is then necessary to resort to graphic representation and to analyze the amplitude, height, time of onset and duration, frequency, and vector of the movements in relationship to the other movements and to the resulting hemodynamics. However, it is easy to follow the systolic and diastolic movements and to interpret the gross mechanical alterations as, for example, the abnormal poststenotic vascular pulsations or the absence of atrial contractions in cases of atrial fibrillation

The study of *cardiovascular hemodynamics* is based on the observation of the progression of the contrast medium through the cardiac chambers and the large vessels, from a densitometric and chronological point of view. The *negative and positive filling defects* and the variations of density of the heart chambers and great vessels, correlated with the chronology of events of the cardiac cycle, are the diagnostic elements. Characteristic is the turbulence produced by the meeting of the blood rendered opaque by the contrast medium with the nonopaque blood. This phenomenon is visible in the superior vena cava at the level of the origin of the azygos vein; in the right atrium adjacent to the orifice of the inferior vena cava or of the coronary sinus; and in the presence of abnormal pulmonary vessels which empty into the atrium or the interatrial defects with left-to-right shunt. Typical is the persistence of the contrast medium in the pulmonary artery in cases of *pulmonic stenosis*, or the reappearance of opacity in it during the levoangiocardiogram due to the left-to-right shunt in cases of *interatrial* or *interventricular septal defects*, in *aortopulmonic shunts*, or in cases with *anomalous venous return*. The angiographic density of the pulmonary artery diminishes cyclically during diastole on the dextroangiocardiogram in *persistence of the ductus arteriosus* (*blanching sign*, Gramiak et al, Campeti). It has been proved that the intensity of this phenomenon is proportional to the magnitude of the shunt. A reflux of the contrast medium in the coronary sinus and the great coronary vein in certain congenital malformations has also been described. Eighty-eight per cent of the patients presented hypertension of the right heart (Campeti). The *incompetence of the aortic valve* may be diagnosed in the LAO view during the last visible cardiac cycle when the left atrium is no longer opaque. In fact, at the end of systole, the ventricular cavity is reduced to its minimum size and its optical density is the same as that of the aorta.

The subsequent reopacification of the left ventricle in diastole can be due only to reflux of aortic blood since the left atrial blood is no longer opaque.

ANALYTICAL DIAGNOSIS

Quantitative evaluation of mechanic and hemodynamic changes recorded by cineradiology is often required in order to define the extent of the cardiovascular alterations This evaluation is possible by correlating the chronology of the events with the changes in motion and radiographic density of the cardiovascular structures, as revealed by the analytical methods devised by the author.

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image-intensifying screen is further perfected. At the present stage of development, the factor of exposure is too high to be ignored in conventional cinefluorographic technique, whereas the pictures recorded by image-intensifying tubes lack detail and definition, aside from the fact that the size of the fluoroscopic field is too small, at least for the investigation of the cardiovascular apparatus.

High-speed cineangiocardiography introduced a new diagnostic element by recording cardiac dynamics and mechanics. The need for understanding them has been felt since the advent of modern cardiac physiopathology. Cardiac catheterization has provided a satisfactory means for investigating hemodynamics However, cardiac mechanics remains a problem, although, after the development of the analytical projector, the author was able to refine his *qualitative* appraisal and conceive a method for graphic *quantitative* analysis of the structural and dynamic events demonstrated in cineangiocardiograms.

Under such conditions, cineangiocardiographic interpretation is no longer a subjective study but the result of an objective analysis of the iconographic and dynamic elements of the examination or, in other words, of the shape and function.

Supported by past experience, the author does not hesitate in concluding that cinefluorography is the technique of the future for the investigation of the human cardiovascular apparatus.

9

Respiratory studies in cardiopulmonary patients

Pulmonary Function Tests

HURLEY L. MOTLEY

Tracings of Pressure and Speed of Respiration

ALDO A. LUISADA AND GIANO MAGRI

Continuous Nitrogen Clearance Technique

OLDRICH PREC

PULMONARY FUNCTION TESTS

Pulmonary function tests are designed to provide accurate information on the extent and type of disturbed lung function, thereby making available additional information for use, with the history and the physical and roentgenological examinations, in the clinical management of the individual cases There is a very intimate relationship between the lungs and the right heart, so that, in treating right heart failure, the pulmonary condition requires primary consideration The essential features of respiration are related to the maintenance of normal tissue-oxygen tension and to an adequate removal of carbon dioxide at all times The adequacy of the blood gas exchange during both rest and exercise can be studied from measurements on lung volumes, arterial blood, and the expired air. One set of measurements provides information on the *bellows action* of the chest and lungs regarding the ability of the individual to move air in and out of the lungs in adequate volumes The other set of measurements provides information on the *blood gas exchange* regarding the transport of oxygen and carbon dioxide across the lungs to the blood

The efficiency of the bellows action of the chest and lungs for moving air in and out of the lungs to the alveoli can be measured from *spirogram tracings* and from *the residual air measurement*. Spirogram tracings provide measurements of total vital capacity, timed vital capacity, maximal breathing capacity and a graphic recording of the exhalation pattern (Fig. 4-137). *Spirogram tracings* record evidence of air-trapping in the lungs when a patient takes repeated deep breaths with rapid exhalation (Fig. 4-137). *Total vital capacity* represents the difference between the volume of the lung *in the maximally distended position* in inspiration and the minimum volume present at the end of a forced exhalation Vital capacity is commonly measured by having the individual take in a deep breath and then blow out the air as far as possible; it may also be measured, however, by having the individual first blow the air out of the lungs as far as possible and then take in as deep a breath as possible In the normal subject there is no significant difference in the *results obtained by* the two methods (Fig 4-137), but in some patients with pulmonary disease the vital capacity measurement obtained by the second method may be larger In either procedure the

image-intensifying screen is further perfected. At the present stage of development, the factor of exposure is too high to be ignored in conventional cinefluorographic technique, whereas the pictures recorded by image-intensifying tubes lack detail and definition, aside from the fact that the size of the fluoroscopic field is too small, at least for the investigation of the cardiovascular apparatus.

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volume difference is measured between maximum inflation and maximum deflation of the lung, and no good clinical evidence exists that measuring the volume difference between maximum deflation followed by maximum inflation is not a valid measure of vital capacity. The level of the diaphragm may shift with position and activity, hence the measurement of vital capacity in separate steps, as the sum of inspiratory reserve and expiratory reserve is subject to error with shifts in the level of the diaphragm and is not satisfactory *A marked reduction in total vital capacity in the standing position as compared to that in the supine position indicates the presence of severe pulmonary insufficiency. In the cardiac patient, the standing vital capacity may be much larger than that in the supine position*

Vital capacity, when recorded with respect to time, becomes a much more significant measurement. The subject is instructed to take in as deep a breath as possible, preferably in the standing position, hold the breath momentarily and then, on command, blow all of the air out of the lungs as rapidly and as completely as possible. The volume exhaled in the first 3 sec, measured from the exact beginning of expiration, is recorded as the 3-sec timed vital capacity (Fig. 4-137). The 3-sec timed vital capacity is normally the same as the individual's predicted total vital capacity (Table 4-12; Fig. 4-138), and is the maximum functional portion of the vital capacity (a respiratory rate of 15 per minute allows 4 sec per breath, but, if 1 sec is utilized for inspiration, only 3 sec are left for expiration) The *timed vital ca-*

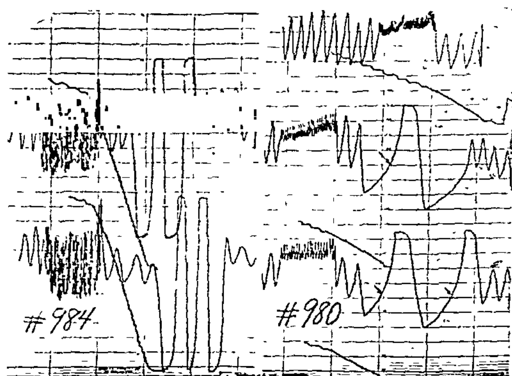


Fig. 4-137. Spirogram tracings of total vital capacity on 13½-liter Collins respirometer. The 3-sec timed vital capacity and the maximal breathing capacity illustrate the characteristic features of a normal tracing (case No. 984) and of one from a patient with severe emphysema (case No. 980); residual represents 61.6 per cent of total lung capacity. The time interval between the vertical lines is 12 sec In case No. 980 with severe emphysema, the total vital capacity was 2,650 ml (64 6 per cent of normal), the timed vital capacity for 3 sec was 1,620 ml (39.5 per cent of normal), and the maximal breathing capacity was 39 0 liters/min (34 0 per cent of normal). The small arrow drawn on tracing No 980 represents the volume of air blown out during the first 3 sec from the exact beginning of expiration The slow exhalation curve obtained after taking a deep breath in No 980 indicates obstruction and a significant degree of pulmonary emphysema. The elevated inspiratory level during the rapid rate of breathing on the tracing for the 12-sec run to obtain the maximal breathing capacity measurement is characteristic of pulmonary emphysema.

pacity may be measured in the first second (normal 75 per cent of total predicted) or in a shorter time interval of 0.5 sec. The shorter time interval provides no significant clinical information and is more difficult to measure (Fig 4-139A).

The characteristic features of the breathing curve are easily observed on the *spirogram recording*. If the exhalation curve on the spirogram tracing is markedly prolonged, except in asthmatic attacks, a significant degree of *pulmonary emphysema* is usually present, but the severity cannot be estimated from the spirogram alone. The spirogram *of a cardiac patient* usually reveals a slight prolongation on exhalation, with decreased amplitude in the absence of emphysema. The spirograms in *emphysema* characteristically reveal a prolonged exhalation time, this is evidence of air trapping and is apparent after a few deep breaths taken in rapid succession, e.g., during the maximal breathing test involving rapid inspiratory movements at a high inspiratory level, since the lungs are kept overinflated in order to decrease breathing resistance as much as possible. The prolonged slow exhalation curve indicates obstruction to air flow, and the failure of the exhalation curve on the tracing in return to the initial level indicates air trapping (Fig 4-137). Pneumotachograms indicate the breathing pattern also, but clinically these do not add to the information obtained from the shape of the spirogram and the timed spirogram exhalation flows and they are more difficult to record and analyze (Fig 4-139B).

The *maximal breathing capacity* reveals the largest volume of air which [illegible]

[illegible] is usually expressed in liters per minute. Individuals should be instructed to breathe as deeply and as rapidly as possible for 12 sec (never longer than 15 sec), and the rate and depth should be varied on successive trials (not less than three) in order to obtain the maximal value (the rate should vary from 80 to 120, if possible to attain).

The 13½-liter Collins *respirometer* was developed to provide an apparatus for mechanical recording with a minimum of breathing resistance to deep fast breathing and to permit quick accurate recordings of the maximal breathing capacity. The drum of the respirometer has a paper

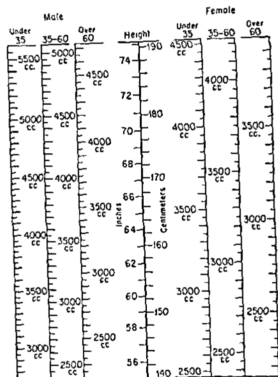


Fig 4-138 Nomogram of predicted vital capacity for height, age, and sex (Motley.)

speed which provides a time interval of 12 sec between the vertical lines (moves 32 mm). Maximal breathing capacity may be obtained by using a high-velocity, low-resistance valve and a 100-liter Douglas bag with a three-way valve, and with 15-sec collection periods. The volume of air has to be measured either with a gas meter or Tissot gasometer. The Douglas-bag method is not as precise or as accurate as the respirometer. The formulas for the predicted maximal breathing capacity, in liters per minute, are

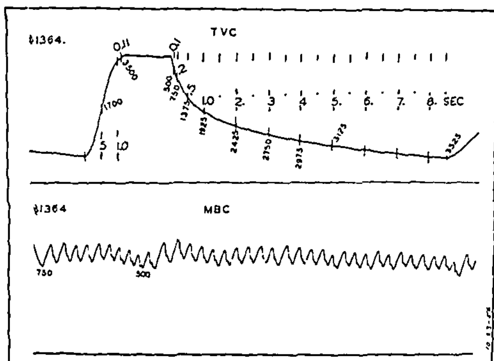
$$\left(97 - \frac{\text{Age}}{2}\right) \text{B S A} \qquad \text{for men} \qquad (1)$$

$$\left(83 - \frac{\text{Age}}{2}\right) \text{B S A} \qquad \text{for women} \qquad (2)$$

where B.S.A. = body surface, m^2
age = years

The standard deviation is 15 per cent. If the 9-liter respirometer is used, the formulas of Cournand and associates should be used for the predicted maximal breathing capacity, as breathing resistance is greater. When the rate and depth of breathing are properly varied, one can obtain precisely the maximal breathing capacity of an individual without introducing the learning factor as such as a significant factor.

The maximal breathing capacity is a measure of the ability to use the lungs and chest



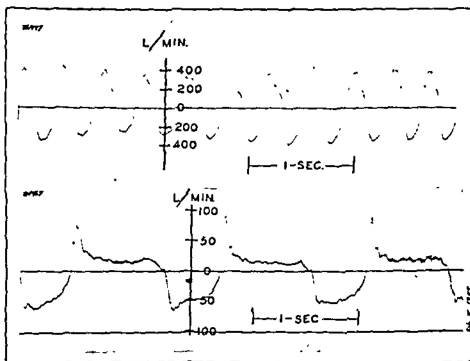


Fig. 4-139. A Rapid recordings of vital capacity (upper) and maximal breathing capacity (lower) with electronic recorder and 13½-liter respirometer attached with helipot to convert volume to electrical output A volume of 3,500 ml was taken in 1 11 sec and 9.0 sec was required to blow out the inspired volume The volume exhaled for 0 1, 0.2, 0 5, 1 0, 2.0, 3 0, 4.0, and 5 0 sec from the exact beginning of exhalation is recorded. The most rapid rate of flow occurs during the first 0.1 to 0.2 sec with a gradually decreasing rate. There is no apparent advantage in using the 0.5-sec or 1.0-sec over the 3-sec volume as all are relative to the maximal flow of the first 0.1 sec. The lower tracing reveals a volume of 500 to 750 ml per breath during the maximal breathing capacity measurement. B Pneumotachograms during deep, fast breathing of a normal flow pattern (above) and of a marked obstructive pattern (below). The calibration scale is in liters per minute. Inspiration is the downward deflection and exhalation the upward. Note the marked prolongation of exhalation in the lower pnumotachogram.

as a bellows and the values spread very widely between the normal and the most abnormal (10 to more than 200 liters/min). If the individual has a normal maximal breathing capacity, he is able to use the diaphragm well, the elasticity of the lungs is good, bronchospasm is not a factor, and there is no significant degree of pulmonary emphysema.

In a selected group of cases with cardiorespiratory disturbances, the total vital capacity varied from 29.7 to 130 per cent of the predicted, the timed vital capacity for 3 sec

TABLE 4-12 PULMONARY FUNCTION MEASUREMENTS IN CARDIORESPIRATORY DISTURBANCES

Case number‖		935	1228	977	1412	1049	1055	221
Age yr, M male, F, female		34, F	37, F	43 F	66, M	38, M	32, M	22, M
Diagnosis	Normal, predicted	R H D † M.S ‡	R H.D M.S	R H.D M.S	R H D. M.S M.I §	Tetralogy of Fallot	Atrial septal defect, P H ¶	Arterio-venous fistula lung, single, large
Total vital capacity, %, predicted	100	107 0	44 7	49 5	62 5	94 5	62 3	78 6
Timed vital capacity, 3 sec, %, predicted	100	88 3	28 0	45 4	60 0	100 1	58 3	78 8
Maximal breathing capacity, %, predicted	100	69 0	28 7	46 2	70 6	126 2	66 0	98 0
Alveolar N_2 % after 7 min O_2 breathing	<1 5%	1 43	1 98	0 63	1 71	0 50	0 70	1 27
Residual air, %, predicted	100	139 3	220 1	138 4	92 5	151 0	112 3	85 7
Total lung capacity, %, predicted	100	115 1	88 5	71 9	71 5	109 0	72 3	80 0
Residual total lung capacity, %	25 *	30 3	62 2	48 1	38 8	35 0	31 1	21 3
Ventilation factor, %	100	74 6	31 6	47 9	69 3	99 2	62 9	90 2
Arterial blood oxygen saturation, %								
At rest, ambient air	96-98	95 3	87.1	93 0	93 1	53 0	83 4	89 0
At rest, IPPB air	98-99		92 2	-	98 5		84 5	
At rest, 42% oxygen	98-100					68 4	86 0	
At rest, 100% oxygen	99-100			100 0	100 0		94 4	90 6
End of exercise, ambient air	96-98	92 5	92 2	93 8	97.5		51 0	86 0
End of exercise, IPPB air	96-98							
End of exercise, 32% oxygen	97-99							
End of exercise, 42% oxygen	98-100							
End of exercise, 100% oxygen	99-100						63 0	
Arterial CO_2 content, vol %								
At rest	48 5	46 0	49 2	45 6	52 5	32 7	37 9	39.4
End of exercise	48 5	44 4	42 9	42 4	44 7		42 9	38.7
Arterial tensions at rest								
P_{CO_2}, mm Hg	40	33	40	41	46	31	35	29
P_{O_2}, mm Hg	95	88	78	85	85	43	68	55
End of exercise								
Minute ventilation, L/min/m² B.S.A.	8-10	9 5	9 51	8.89	13 48		10 5	15 6
Oxygen uptake, ml/min/m² B.S.A.	500-600	451	340	215	318		218	654
Oxygen, % extracted from air	3-6	4 72	3 58	2 42	2 36		2 08	4 19
Effective tidal air at rest, %	75	80 0	60 0	53 2	48 3	51 0	50 4	77 0
Dyspnea duration, sec, after 1-min step-up exercise	<90	50	145	85 0	132		167	60

* Under 35 yr 20%, over 60 yr 30%
† R.H.D., Rheumatic heart disease
‡ M.S., Mitral stenosis
§ M.I., Mitral insufficiency
¶ P.H., Pulmonary hypertension (catheterization)
Case no. 935 Mitral commissurotomy performed satisfactorily
Case no. 1228 Mitral commissurotomy performed satisfactorily after pulmonary condition treated with IPPB and bronchodilators 14 months
Case no. 977 Died at surgery, ball valve thrombus
Case no. 1412 No surgery performed
Case no. 1055 Unsatisfactory for surgery septal defect acts as safety valve, unable to increase exercise pulmonary blood flow adequately
Case no. 221 After left lower lobectomy, blood gas exchange normal

from 28.0 to 104.7 per cent, and the maximal breathing capacity from 26.7 to 126.2 per cent (Table 4-12).

The degree of bronchospasm is measured quantitatively by comparing the maximal breathing capacity measurement before and immediately after one bronchodilator treatment using a potent bronchodilator substance, such as *Isuprel* or *Vaponefrin*. The maximal breathing capacity and the timed vital capacity are independently variable measurements. It has been found in men that, if the maximal breathing capacity is above 120 liters/min, the degree of pulmonary emphysema present is insignificant while, on the other hand, if the maximal breathing capacity is less than 40 liters/min, a significant degree of pulmonary emphysema is present. Between 40 and 120 liters/min the values have *an indeterminate* significance.

The test for maximal breathing capacity is a sensitive one and, since this measurement fre-

TABLE 4-12 PULMONARY FUNCTION MEASUREMENTS IN CARDIORESPIRATORY DISTURBANCES (*Continued*)

Case number	654	1238	1029	1465	1464	1418	1398
Age, yr, M, male, F, female	30, *F*	40, *F*	55, *F*	47 *F*	52, *M*	63, *M*	37, *F*
Diagnosis	*Arteriovenous fistula lung, multiple, small*	*Arteriovenous fistula, lung, multiple, large*	*Emphysema, bronchiectasis*	*Emphysema*	*Pulmonary emphysema and tuberculosis*	*Lung cyst, large*	*Fibrosis, lung*
Total vital capacity % predicted	100.6	115.0	56.1	89.5	29.7	130.0	43.7
Timed vital capacity, 3 sec, %, predicted	98.1	112.0	45.9	50.2	33.8	75.1	47.7
Maximal breathing capacity, %, predicted	87.1	123.0	63.6	36.2	28.6	58.8	69.8
Alveolar N_2, % after 7 min O_2 breathing	0.77	0.53	2.53	5.49	6.00	3.49	0.63
Residual air %, predicted	89.6	116.0	158.8	356.0	143.0	152.4	69.9
Total lung capacity %, predicted	98.4	116.0	81.7	150.0	58.1	136.7	50.0
Residual total lung capacity %	18.2	25.1	48.7	57.0	61.6	33.4	34.5
Ventilation factor, %	98.3	111.6	53.6	43.4	34.3	74.6	70.0
Arterial blood oxygen saturation, %							
At rest, ambient air	67.6	64.8	92.7	94.1	94.4	90.6	96.0
At rest, IPPB air	87.5		96.0	95.0	96.8	96.7	
At rest, 42% oxygen	92.4	69.0					
At rest, 100% oxygen	97.2	75.5	98.9	99.3	98.4	99.4	99.0
End of exercise, ambient air	72.0	54.8	91.8	93.6	94.5	86.5	83.5
End of exercise, IPPB air			89.2				
End of exercise, 32% oxygen			91.3		95.2	92.0	86.8
End of exercise, 42% oxygen							
End of exercise, 100% oxygen		64.3					96.0
Arterial CO_2 content, vol %							
At rest	37.7	36.9	50.8	48.7	48.7	43.9	44.6
End of exercise	36.0	35.2	48.1	40.3	43.6	42.2	41.7
Arterial tensions at rest							
P_{CO_2}, mm Hg	29	32	58	39	44	40	31
P_{O_2}, mm Hg	81	48	75	81	97	69	90
End of exercise							
Minute ventilation, L/min/m² B.S.A	17.0	15.5	8.2	12.9	11.6	12.5	12.2
Oxygen uptake, ml/min/m² B.S.A	508	379	394	389	448	386	357
Oxygen, % extracted from air	2.99	2.45	4.81	3.03	3.85	3.10	3.92
Effective tidal air, at rest, %	63.0	48.3	56.0	63.0	59.3	51.6	85.4
Dyspnea duration, sec, after 1-min step-up exercise	123	109	195	190	50	80	90

Case no 654 Diagnosis demonstrated by plastic injection of lung post mortem, lung biopsy and angiograms negative during life
Case no 1238 Pulmonary angiograms show multiple, large, arteriovenous fistulas in all lobes
Case no 1464. Evaluation study for surgery, for decortication

quently reveals early pulmonary abnormalities, it is valuable for screening purposes. Spirogram recordings are easy to perform. The tests can be done in an office in 10 to 15 min. When the degree of bronchospasm is evaluated, a slightly longer time is required, since the bronchodilator drug should be administered (preferably with an intermittent positive pressure breathing apparatus) for a period of 5 or 10 min to obtain the maximal response

The second important basic measurement relating to the bellows action of the chest and lungs is the *residual air*, which is the air remaining in the lung at the end of a forced exhalation The residual air normally occupies about 25 per cent of total lung capacity, being slightly smaller in the younger age group, 20 per cent up to 35 years of age, slightly larger in the older age group, and 30 per cent over 60 years of age. The author's studies indicate that in normal individuals even up to 70 years of age and beyond, the residual air is not above 35 per cent of total lung capacity. Pulmonary emphysema is frequently missed in the chest roentgenogram when a severe degree actually exists. If two criteria are

TABLE 4-12 PULMONARY FUNCTION MEASUREMENTS IN CARDIORESPIRATORY DISTURBANCES (*Continued*)

Case number	1428	1041	1093	1376	1441	1040	797
Age yr, M, male, F, female	32 F	44 M	36, M	65, M	63, M	58 M	55, M
Diagnosis	Sarcoidosis, S.N.B. (+)[a]	Berylliosis chronic	Hyperventilation	Hyperventilation	Polycythemia	Asbestosis	Diatomite, pneumoconiosis
Total vital capacity, %, predicted	30.8	39.4	94.9	92.4	112.0	56.8	52.1
Timed vital capacity, 3 sec, %, predicted	31.2	42.3	104.7	86.2	103.0	56.8	32.0
Maximal breathing capacity, %, predicted	75.9	58.1	108.0	88.4	120.0	73.7	21.9
Alveolar N_2, % after 7 min O_2 breathing	1.59	0.61	1.32	0.68	0.41	1.22	2.78
Residual air %, predicted	57.1	131.1	77.7	111.0	80.3	126.1	221.4
Total lung capacity %, predicted	40.7	67.7	90.6	98.0	103.1	74.1	94.4
Residual total lung capacity %	28.0	45.4	21.4	34.0	23.4	42.5	58.6
Ventilation factor %	60.5	48.2	109.8	87.6	114.0	63.1	32.2
Arterial blood oxygen saturation %							
At rest, ambient air	87.8	83.5	83.5	97.1	91.7	94.0	89.5
At rest, IPPB air	92.0	89.0	96.0		98.6	96.5	91.0
At rest, 42% oxygen		97.5					
At rest, 100% oxygen	99.0	99.4	98.5		100.0	99.6	97.3
End of exercise ambient air	71.6	60.8	76.1	98.4	96.5	82.0	83.7
End of exercise IPPB air			94.0			83.5	
End of exercise, 32% oxygen	78.2		97.7			90.5	
End of exercise, 42% oxygen	82.5						
End of exercise, 100% oxygen							92.2
Arterial CO_2 content, vol %							
At rest	48.0	48.4	61.0	37.5	42.7	45.5	60.3
End of exercise	44.5	44.6	59.7	39.7	38.9	45.8	58.9
Arterial tensions at rest							
P_{CO_2} mm Hg	47	43	67	33	35	44	56
P_{O_2} mm Hg	67	61	65	112	65	85	66
End of exercise							
Minute ventilation, L min m² B.S.A.	12.4	20.1	6.0	11.0	16.1	10.0	8.1
Oxygen uptake ml min m² B.S.A.	371	237	409	447	635	403	331
Oxygen, % extracted from air	2.99	2.01	6.75	4.06	3.96	4.02	4.07
Effective tidal air at rest, %	59.0	38.6	69.0	50.8	62.4	63.0	52.7
Dyspnea duration, sec, after 1-min step-up exercise	100	310	25	100	130	84	116

[a] S.N.B., Scalene node biopsy + sarcoid

Case no. 1041: Neon-tube bender 15 yr

Case no. 1040: Asbestos worker 35 yr

used, regardless of age, (1) a normal maximal breathing capacity; and (2) a normal timed vital capacity, in the author's experience the residual air has not been found above 35 per cent of total lung capacity, so that emphysema is not necessarily part of the normal aging process. There are many people, with a residual air value above 35 per cent of total lung capacity, who are capable of doing their job with no complaint. This is because the lung reserve is normally so large that, when subjective complaints of dyspnea are present, the pulmonary changes are already in an advanced state. A residual air value above 35 per cent of total lung capacity is abnormal, just as a blood pressure of 200 is abnormal, even though the individual may have no subjective complaints.

Residual air is measured quantitatively using the *oxygen open-circuit method* or the *helium closed-circuit method* (both methods have been found satisfactory, giving values which check within 2 per cent) The alveolar nitrogen should normally be less than 1.5 per cent after the subject has been breathing oxygen for 7 min. An elevated alveolar nitrogen value indicates impairment in the uniformity of air distribution in the lungs. Impairment in air distribution in the lungs can also be measured by using the nitrogen meter with a single deep breath, but rather elaborate and expensive equipment is required (Fig. 4-140). The use of the nitrogen meter with continuous recording of the washout on oxygen breathing provides essentially the same information as the residual air measurement, although in some cases the tracing alone is not as exact; for example, in large cysts of the lung, the severity of the emphysema may appear much greater than it actually is, according to the quantitative measurement of residual air and spirograms.

The three independent variable measurements of pulmonary function already described that are of greatest importance relating to the bellows action of the chest and lungs are: (1) *The timed vital capacity for 3 sec,* (2) the

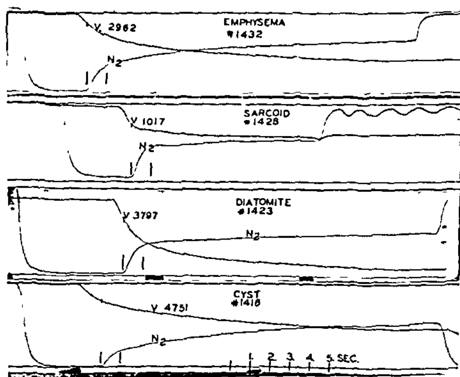


Fig. 4-140. The nitrogen curve (labeled N_2) and the corresponding volume (V) and flow during exhalation (total recorded as ml) obtained by taking a single deep breath of oxygen and then blowing out as much as possible. The nitrogen was recorded from a nitrogen meter and the volume from the respirometer as given in Fig 4-139. Normal intrapulmonary mixing produces quickly a flat plateau as shown in case No. 1428 (sarcoidosis). Impaired intrapulmonary mixing gives a prolonged sloping curve upwards as shown in cases No. 1432 (severe emphysema) and 1418 (diagnosis, large pulmonary cyst). There is a moderate degree of emphysema present in case No. 1423 (diatomite pneumoconiosis) and the curve is intermediate.

maximal breathing capacity, and (3) the residual air as per cent of total lung capacity. A numerical ventilation factor (VF) has been used to evaluate the efficiency of the chest and lungs as a bellows from the average of the three measurements, all expressed as per cent of the normal predicted, namely: the 3-sec vital capacity, the maximal breathing capacity, and the residual air as per cent of total lung capacity. The ventilation factor provides a single significant numerical value of the patient's ability to use the chest and lungs as a bellows for aerating the alveoli, and this is correlated well with the arterial P_{CO_2} in millimeter of Hg as determined by direct tension measurements of arterial blood, an independent measurement.

In the selected group of patients with a variety of types of cardiorespiratory disturbances (Table 4-12) the alveolar N_2 varied from 0.41 to 6.0 per cent, the residual air from 57.0 to 356.0 per cent of the predicted, the total lung capacity from 41.0 to 156.0 per cent, the residual per cent of total lung capacity from 18.2 to 62.2 per cent, and the ventilation factor from 31.0 to 114.0 per cent.

The second basic aspect of pulmonary function is *the blood gas exchange across the alveolocapillary membrane*, and thus is evaluated from studies of the arterial blood and the expired air. The hemoglobin in the arterial blood is normally 96 to 98 per cent saturated with oxygen both at rest and during exercise at sea-level pressure. The arterial blood oxygen saturation is obtained by dividing the corrected oxygen content by the corrected oxygen capacity in volume per 100 ml for each sample of blood. The *van Slyke manometric apparatus* is used for the measurement of oxygen content and capacity. The *double-scale Waters oximeter, using the cuvette and whole blood*, has been found a satisfactory device for determining the oxygen saturation of arterial blood, and, in general, when properly calibrated, checks within 1 per cent the measurement with the van Slyke apparatus.

... the vessels exposed to atmospheric pressure. The blood flow through the lungs takes the path of least resistance and apparently *selective diversion of the flow* of blood occurs from regions with high vascular resistance to areas with lower resistance. Many patients with extensive lung disease, as revealed by the chest roentgenogram, have surprisingly good arterial blood saturations at rest, the *blood flow* being diverted through the better ventilated and perfused areas. Mild exercise may reveal gross abnormalities because of increased cardiac output and loss of the selective *diversion of flow*. *The great distensibility of the pulmonary* capillary bed and its large surface area (approximately 100 m^2) tend to reduce flow resistance to a minimum. The thin pulmonary capillaries have been described as virtually *hanging in space*, thus providing a maximum surface area of contact for gas exchange, especially of oxygen with the hemoglobin as the red blood cells flow by in single file. This intimate contact of oxygen and hemoglobin is necessary if all the hemoglobin is to be converted to oxyhemoglobin for, once beyond the capillaries, the piling up of red blood cells (4 to 5 million/mm^3) offers mechanical barriers to full saturation of all the hemoglobin, even though the oxygen tension is adequate. *Direct tension measurements* provide the only reliable measurements of arterial P_{O_2} in cardiorespiratory disturbances with shunting of blood from right to left and the presence of poorly ventilated alveoli (Table 4-12, Fig. 4-141; the oxyhemoglobin dissociation curve does not hold here).

A decrease in the oxygen saturation of arterial blood may be due to (1) a diffusion difficulty at the alveolocapillary membrane, (2) shunting of blood through nonventilated areas either in the lung or in the heart, or (3) poorly ventilated alveoli. In general, in most cases of chronic pulmonary disease due to fibrosis and emphysema, there is little evidence of a true diffusion difficulty at the alveolocapillary membrane, such as typically occurs in berylliosis (Table 4-12). The common finding in *chronic pulmonary disease* due to emphysema and fibrosis is the presence of poorly ventilated alveoli and, when a decrease in saturation occurs with exercise, it is principally due to shunting of blood through nonventilated or poorly ventilated areas. A *reduced diffusing capacity* of the lungs may be due to any of several factors and does not necessarily involve an increased difficulty in the diffusion of oxygen at the level of the alveolocapillary membrane. In most of the author's cases, the oxygen

crossed the alveolocapillary membrane in proportion to the individual partial pressures of the alveoli.

A simple test to demonstrate shunting from right to left employs high-oxygen breathing in a graduated series, such as 32 or 42 per cent oxygen in contrast to 100 per cent oxygen which tends to obscure multiple small areas of shunting in the lungs (Table 4-12). The inspired oxygen tension is increased over 70 mm

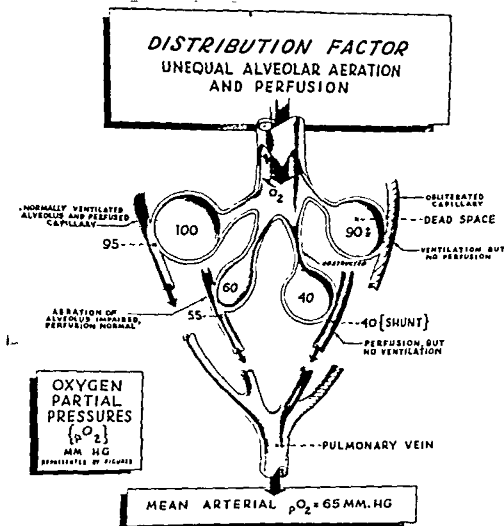


Fig. 4-141. A schematic diagram indicating the disturbed relationship between alveolar aeration and perfusion which is characteristic of chronic pulmonary disease. When the partial pressure of oxygen is 100 mm Hg in the alveolus, normally the blood is fully saturated (96 per cent or more). If the aeration of the alveolus is impaired, as shown above, the partial pressure of oxygen is reduced and the blood perfusing the alveolus can pick up oxygen only in proportion to the partial pressure, hence the blood is only partially saturated. If the impaired aeration of the poorly ventilated alveoli can be improved, as with intermittent positive-pressure breathing on compressed air only, the saturation of the blood perfusing the poorly ventilated alveolus will be increased. If alveolar aeration is completely blocked, this unit becomes a small shunt with perfusion but no ventilation (shunting at the alveolar level). Impaired aeration and perfusion in varying degrees may exist in a given case. If a diffusion difficulty exists, a larger difference in the oxygen partial pressure is present between the alveoli and the arterial blood with unsaturation. Alveoli which are ventilated but not perfused because of obliteration of the blood supply represent dead space. Elevating the partial pressure of the inspired oxygen (e.g., by breathing 32 per cent oxygen) corrects for diffusion difficulties and for the decrease in P_{O_2} due to unequal alveolar aeration. However, in shunts in the pulmonary circulation or in the heart, breathing 32 per cent oxygen does not increase the saturation to normal, and even breathing 100 per cent oxygen in the presence of larger shunts does not completely saturate the hemoglobin to 100 per cent. (From Motley, 1950.)

Hg on a 32 per cent oxygen breathing mixture, which is large enough to overcome a diffusion difficulty at the alveolocapillary membrane, if *that is the primary* difficulty on air breathing. *A decrease* in arterial saturation with moderate exercise occurs often in *fibrosis* and *emphysema* and *right-to-left shunts* in the heart or lungs, and the exercise saturation does not go up to normal even on high-oxygen breathing (32 per cent oxygen) demonstrating the absence of a diffusion difficulty (Table 4-12).

Another simple test employed in determining the nature of arterial unsaturation is the use of *intermittent positive pressure breathing* with compressed air (no bronchodilators). In most cases of fibrosis and emphysema, a significant rise in the saturation, sometimes up to normal, results from pressure breathing on compressed air alone, and the only way to explain this finding is on the basis of the presence of poorly ventilated alveoli, with the pressure breathing providing improved aeration (Table 4-12). The pressure breathing at rest on air does not elevate the inspired P_{O_2} to a sufficient degree to be a factor in overcoming any diffusion difficulty present at the pulmonary membrane Pressure breathing produces no significant change in the resting ar*terial blood* oxygen saturation in patients with *proved right-to-left* shunts in the lung such as *arteriovenous fistula* (Table 4-12). The improved saturation with pressure breathing on compressed air indicates the presence of *alveoli* which are poorly ventilated on ambient *air breathing* (Fig. 4-141)

If the lowering of the oxygen saturation of *arterial blood* resulting from exercise arose from a diffusion difficulty, then the *high-oxygen breathing (32 per cent O_2)* with the increased *inspired P_{O_2} (over 70* mm *Hg)* would restore the blood saturation to a normal level of 97 per cent or more During step-up *exercise tests* on a high-oxygen breathing *mixture* (32 0 per cent O_2), in cases of *emphysema*, the *arterial* blood-oxygen saturation is still *abnormally low.* These data indicate that, during step-up exercise tests with *increased cardiac* output from the right side of the *heart, some blood* bypasses ventilated alveoli with *shunting*, a condition which the *high-oxygen breathing* mixture does not correct Even breathing 100 *per cent oxygen* does not elevate the *saturation to the normal* level of 99 per cent or more in all *cases* of severe pulmonary insufficiency. In pulmonary fibrosis and emphysema in general, the *lowering of the oxygen* saturation of arterial blood which occurs both at rest and with exercise results from alterations in the ventilation-perfusion relationship The *following* abnormalities are present: *(1) some alveoli* are poorly aerated yet perfused either normally or with a decreased amount of blood; (2) other alveoli are perfused but not aerated (this latter condition represents a *small shunt at the* alveolar level), and (3), some alveoli are ventilated but not perfused with blood (Fig. 4-141) The increase *during* exercise, noted in the oxygen saturation of arterial blood in some patients, is comparable to that produced by intermittent positive-pressure breathing on compressed air only, and represents a more uniform alveolar aeration provided by exercise through deeper breathing and increased tidal volume.

A *decrease* in the oxygen saturation of arterial blood to 5 to 10 per cent or more below the resting level with exercise indicates the presence of severe disability and the patient should avoid walking up steps. If oxygen saturation increases after exercise to a value above the resting level, this is an indication of less disability than is implied by the resting level measurement. The resting and postexercise oxygen saturation of arterial blood should be compared in each case, if possible, because often the saturation after exertion is of much greater significance than the resting values in evaluating the status of pulmonary function. The one-minute step-up test (30 steps in 1 min on an 8-in. stool) has been found satisfactory for clinical evaluation The step-up test for 1 min is a mild exertion for the normal individual and is not designed as a test of physical fitness

An elevated CO_2 content in arterial blood indicates inadequate alveolar aeration and pre*dicts the possibility* of respiratory acidosis dur*ing infections or* a depression of respiration by breathing oxygen at ambient pressure, sedatives, drugs, anesthetics, or other means. If the patient has a marked degree of oxygen unsaturation of arterial blood, together with an elevated CO_2 content, then the administra*tion of* high oxygen concentrations with a mask, catheter, or tent may precipitate respiratory aci*dosis, drowsiness,* coma, or even death. In such

a patient, the sudden change to high-oxygen breathing relieves the arterial blood unsaturation and inhibits the stimulation of the respiratory center by the carotid bodies, which are activated by low oxygen tension of the blood. The ventilation per minute decreases in some cases to critical levels unless supplemented by mechanical aids. The P_{CO_2}, as calculated from the oxygen capacity of arterial blood, pH, and CO_2 content, reveals an unsatisfactory correlation when compared with the direct tension measurement of arterial P_{CO_2}. In general, the calculated P_{CO_2} was too low.

The *direct determination of arterial blood pH* is necessary to accurately determine the exact status of acidosis or alkalosis in patients with a severe degree of pulmonary insufficiency. Conversely, the calculated pH value is unreliable in patients with severe pulmonary disease. The direct determination of arterial blood pH by means of glass electrodes provides an accurate measurement of H+ ions, and takes the guesswork out of the status of acidosis or alkalosis in the treatment of both cardiac and pulmonary patients.

Since an adequate minute ventilation and pulmonary blood flow are the two factors necessary to remove from the lung an amount of oxygen corresponding to the exercise taken, when the ventilation is adequate and the exercise oxygen uptake is reduced, the existence of decreased pulmonary blood flow should be admitted A marked decrease in oxygen uptake upon exertion was observed in cases of congenital heart defects with atrial septal defects and pulmonary artery hypertension (Table 4-12). The inability to increase the pulmonary blood flow during exercise because of increased vascular resistance and lack of expansibility of the pulmonary bed is characteristic of pulmonary fibrosis and emphysema, and the decreased oxygen uptake is easily demonstrated by the 1-min step-up test. The lowest exercise oxygen uptake presented in Table 4-12 was 215 ml/min/m² B S.A in a cardiac patient with rheumatic heart disease and mitral stenosis, while in a patient having a single large arteriovenous fistula of the lung the value was normal (654 ml/min/m² BSA)

The proportion of oxygen (calculated in per cent) extracted from the inspired air breathed is markedly decreased in some cardiac patients, in cases of right-to-left shunts and of chronic pulmonary disease (Table 4-12). This test is a measure of the lung ventilation efficiency, sometimes expressed as ventilation equivalent (liters of air required to supply 100 ml of oxygen). The effective tidal air was calculated from the expired P_{CO_2} and the arterial P_{CO_2} and it may vary markedly as shown in Table 4-12 (38.6 to 80.0 per cent).

Dyspnea time following step-up exercise for 1 min was quite variable (Table 4-12). *Dyspnea,* when prolonged in the absence of significant changes in lung-volume measurements, indicates the presence of a cardiac factor. Since dyspnea is a subjective measurement, the evaluation has limitations.

In evaluating for surgery cardiac patients with pulmonary hypertension and septal defects, the resting and exercising (step-up) arterial saturation with air and oxygen breathing should be obtained. The oxygen uptake during exercise with air breathing is also necessary. The data on the following case illustrate the importance of these measurements.

A 45-year-old man, with an atrial septal defect and pulmonary artery systolic pressure of 60 mm Hg, by means of right heart catheterization was shown to have oxygen saturations of arterial blood as follows: resting, on air 88.3 per cent, on 100 per cent O_2, 100 per cent, step-up exercise, on air 89 per cent, on 100 per cent O_2, 92 per cent. Although the ventilation was increased with exercise, the oxygen uptake was markedly to very markedly decreased, 310 ml/min/m², B.S.A. (normal 500 to 600) These data indicate that during exercise the pulmonary blood flow was increased very little as compared to the resting flow and the septal defect was acting as a safety valve for right-to-left shunting with the increased cardiac output during exercise Surgery was carried out for closure of the septal defect. Following the operation, the right ventricle dilated, massage was ineffective in forcing blood through the pulmonary bed, and death resulted.

In conclusion, a battery of test measurements is necessary to provide accurate information on the extent and type of disturbed cardiorespiratory function in the individual case regardless of the causation No single test is satisfactory for the accurate and complete clinical evaluation of the extent of pulmonary function impairment. The large pulmonary reserve in man often prevents clinical or roentgenographic detection of early pathological changes before clinical symptoms become prominent.

TRACINGS OF PRESSURE AND SPEED OF RESPIRATION

Following studies of graphic tracings of *external respiratory motions,* several authors investigated *the changes of lateral pressure* from one of the nostrils or from the mouth during normal respiration. These were recorded at *first on a smoked* drum by means of a Marey tambour, then on photographic film by means *of a Frank's capsule;* last, on the film of an electrocardiograph by a crystal microphone.

The velocity of the air from the mouth was studied first by Fleisch, who described a *special instrument, the pneumotachograph.* This, based on the principle of a differential Frank's *capsule, recorded the tracing by means* of a mirror fastened on the membrane *inside* the *capsule;* both the direct and the reflected beams passed through the glass closing the *capsule. Another, less perfect pneumotachograph* was described by Hochrein Pneumo*tachographic tracings of normal* subjects were studied by Bretschger. Both the original *method of Fleisch and a new method, based* on a pneumotachograph and a differential crys*tal microphone, were used by the author.*

TECHNIQUE

Tracings of Pressure. A rubber tube having a lumen *of 3 mm is connected with a glass or* bakelite olive at one end and with a linear, piezoelectric *microphone at the other. The olive is* introduced into one of the nostrils of the *patient, who is instructed to breathe* evenly through the nose The jack of the *microphone is connected with the input of* an electrocardiograph and the tracing is recorded either *photographically or by direct*-writing methods. The *zero line* is found by asking the patient *to hold his breath for a few* seconds during apnea, irrespective of the phase of *respiration in which the chest is* immobilized, the light beam (or the pen) traces a straight line which *is the zero line If the* subject has some impairment of nasal respiration, a mouthpiece, like that used *for determination* of the basal metabolic rate, is placed in the mouth of the subject *It is connected* with a short, open piece of tubing having a thin metal tube on one *side. The latter is connected* with a linear microphone and the patient is instructed to breathe *evenly through* the mouth. *If necessary, a nose clamp is used* in order to prevent nasal respiration.

Tracings of Velocity. Fleisch's pneumotachograph is made as follows: A series of thin tubes having a lumen of 3 mm is contained inside a larger metal tube ending in a mouthpiece. Two side-tubes, opening in one of the thin tubes, are connected by short rubber tubes with *a differential linear microphone* connected with the electrocardiograph The proximal tube is connected with that end of the microphone which gives a positive deflection for an increase in pressure, the distal tube, with the other end. The *mouthpiece* of the pneumotachograph is placed in the patient's mouth. If necessary, a nose clamp is used in order to prevent nasal respiration. At some time while the record is being taken, the patient is invited to hold his breath. The light beam or the pen *of the electrocardiograph then traces a steady* line which represents the zero line of the *tracing.*

Objections may be raised against the use of *the linear microphone for either* velocity or pressure curves of respiration because it does *not register extremely slow deflections. However,* respiratory waves are still within the *field of action of this microphone and only* a minimal deformation of the curve may be expected, *consisting of a slightly* earlier flattening of the curve at the end of each phase. In *order to avoid displacement of the base line,* no use of the "instomatic" device for automatic *adjustment of the tracing should* be made during the entire test.

ANALYSIS OF WAVES

Both the pressure and the velocity tracing consist essentially of two rounded, diphasic waves During *inspiration,* the curve drops, then slowly flattens and returns to the zero line. *Expiration* is not separated from inspiration by an accident of the tracing; only the zero line, artificially traced, divides the two phases. During *expiration,* the tracing rises slowly above the zero line, reaches a maximum, then slowly tapers off and again reaches the zero line. Expiration is somewhat longer than inspiration and may become much longer if pathological changes are present. Small notches, due to

a patient, the sudden change to high-oxygen breathing relieves the arterial blood unsaturation and inhibits the stimulation of the respiratory center by the carotid bodies, which are activated by low oxygen tension of the blood. The ventilation per minute decreases in some cases to critical levels unless supplemented by mechanical aids. The P_{CO_2}, as calculated from the oxygen capacity of arterial blood, pH, and CO_2 content, reveals an unsatisfactory correlation when compared with the direct tension measurement of arterial P_{CO_2}. In general, the calculated P_{CO_2} was too low.

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It is the function of *the alveolocapillary unit* to maintain the optimum tensions of oxygen and carbon dioxide and the normal pH of the blood under varying metabolic loads. Its failure to do so may be caused by three different mechanisms, (1) unequal distribution of inspired air into alveolar space; (2) change in physical properties of the alveolocapillary membrane with impairment of diffusion, and (3) abnormal alveolar ventilation/perfusion ratio. Although normal tidal volume and normal respiratory rate are necessary conditions for adequate alveolar ventilation, uniform distribution of the tidal air into all alveoli constitutes the final mechanism by which rapid alveolar ventilation is achieved. This mechanism has proved to be extremely vulnerable If it is deranged, groups of alveoli with excessively rapid ventilation will coexist in the same lung with areas of abnormally slow ventilation, despite normal or even increased volume of minute ventilation. The relative magnitude of these areas, their number, and the speed of turnover of the gas molecules within these subdivided spaces constitute *the alveolar ventilatory pattern* With this concept in mind, it is easily understood that even severe degrees of alveolar hypoventilation may be undetected if only the minute volume of ventilation is measured.

Methods utilizing the dilution principle with foreign gases i e, oxygen and helium (Cournand et al.; Bateman), seem to be most suitable for the study of the distribution patterns, because they are independent of diffusion and perfusion Furthermore, they cause little discomfort to the patient and are easily adaptable to various physiological and pathological conditions A nitrogen clearance technique, using oxygen as the diluting gas and the rapid nitrogen meter for breath-to-breath analysis of the alveolar air will be described

TECHNIQUE

Equipment (see Fig 4-144A) An oxygen tank, fitted with a demand valve, is connected through large-diameter rubber tubing with a five-way respiratory valve The expiratory outlet of the valve is connected with a spirometer of 120-liter capacity equipped with a kymograph It has been found advantageous to insert large unidirectional valves into the inlet and outlet tubing close to the five-way valve in order to reduce the degree of compression of oxygen in the inspiratory tubing

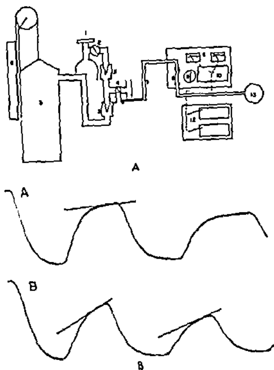


Fig. 4-144. A. Apparatus to determine nitrogen clearance. 1, oxygen tank; 2, respiratory demand valve, 3, unidirectional respiratory valves; 4, 5-way respiratory valve, 5, spirometer; 6, kymograph; 7, sampling needle and inlet tubing to the nitrogen meter, 8, cathode tube, 9, phototube; 10, amplifier; 11, monitoring galvanometers; 12, recorder, 13, vacuum pump. B Instantaneous recording of nitrogen concentration during a single breath of oxygen A, alveolar plateau B, alveolar slope.

during the early phase of expiration, when it is necessary to overcome the inertia of the spirometer The subject is connected with the five-way valve through a conventional rubber mouthpiece The sampling needle of the nitrogen meter is inserted into the rubber mouthpiece just outside the lips of the subject The whole system of tubing and spirometer is washed out several times with pure oxygen, and the nitrogen content of the last washout is routinely checked by the nitrogen meter. It should be identical with the nitrogen content of the oxygen tank and should not exceed 0 1 per cent. The dead space of the spirometer is determined in advance and is kept constant by maintaining the water level at the same mark

The response of the nitrogen meter is not linear, and the meter has to be calibrated before each determination with mixtures of 20, 40, 60, and 80 per cent of nitrogen in oxygen. These mixtures can be obtained in cylinders, but accurate composition has to be determined by either the Haldane

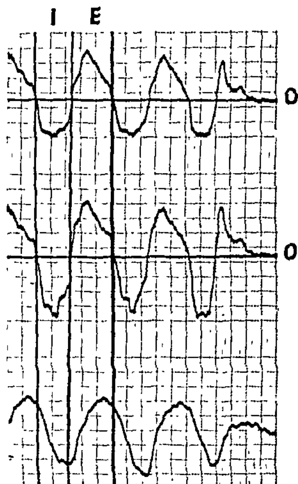


Fig. 4-142. Pneumotachogram (above) compared with a pressure tracing from the mouth (center) and a thoracic external tracing of respiration (below); *I*, inspiration; *E*, expiration. (*From A. A. Luisada. Heart Beat, Hoeber, 1953*)

cardiac action, are present in both phases

As shown in Fig. 4-142, there is but a small difference between the pressure and velocity tracings. Therefore, except in special cases, the first type of tracing should be preferred for clinical studies, since it is easier to record.

Inspiration is accompanied by a decrease of pressure in the respiratory passages; this causes suction of air and a drop in both the pressure and the velocity tracings. Expiration is accompanied by an increase of pressure in the respiratory passages; this causes expulsion of air and a rise in both the pressure and the velocity tracings. The time relationship between these waves and the external movements of respiration is apparent in Fig. 4-142. The end of inspiration is revealed by the lowest point of the curve of external respiration and by a return to the zero line of the curves of pressure and velocity. The end of expiration is revealed by the highest point of the curve of external respiration and by the return to the zero line of the curves of pressure and velocity

Pneumotachography has been used for various physiological studies, including one on cardiac output, which have lost value since. Clinical tracings of pressure are accurate and present some interest in the differential diagnosis of the various forms of dyspnea. In particular, when expiration is greatly prolonged, the ratio of this phase to inspiration is very well revealed by the tracing (Fig 4-143).

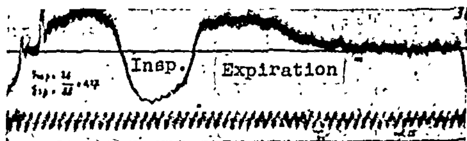


Fig. 4-143. Pneumotachogram of a patient with bronchial asthma showing extreme increase of expiration.

CONTINUOUS NITROGEN CLEARANCE TECHNIQUE

An integrated and concise concept of the alveolus with surrounding capillaries as a functional unit was developed by Henderson and his collaborators (1928). The clinical application of the basic principles governing the gas exchange between alveolar air and capillary blood, however, has been considerably delayed because of inaccessibility of these structures for direct evaluation Only after development of cardiac catheterization and of rapid gas analyzers has quantitative evaluation of various functions within such a unit become feasible.

or Roughton-Scholander method. The calibration mixtures must be saturated with water, because the calibration curve of water-saturated gases differs

A two-

oscillo-

he sensi-

tivity of the first channel is calibrated for a range of 0 to 80 per cent nitrogen concentrations and the second channel for a range 0 to 12 per cent

sufficient accuracy.

The procedure is explained to the subject, who is then fitted with a nose clip and begins to breathe through the mouthpiece and through one side of the five-way valve which is connected to the room air. After a few minutes of air breathing the valve (at the end of normal expiration) is switched to the oxygen circuit. From this point on, the subject breathes from the oxygen tank and the expired gas is collected in the spirometer. The nitrogen concentration is monitored on the galvanometer of the meter and, when it decreases to 10 to 11 per cent, the meter is switched to the second recording channel. The procedure continues until the concentration decreases to 0.2 per cent, or less, time is marked every one-half minute on the graph.

The gas in the spirometer is analyzed for nitrogen content and the functional residual volume is calculated from these data by the method of Darling et al. (1940). The kymographic record is inspected for variations in minute volume.

Treatment of Nitrogen Clearance Data. Two different patterns of continuous nitrogen concentration during a single breath are encountered (Fig. 4-144B). The first pattern is seen predominantly, but not exclusively, in normal lungs, and is characterized by the presence of a horizontal plateau. This part of the curve represents a close approximation of the nitrogen concentration of the alveolar air. In the second pattern, which in the author's experience is encountered only in abnormal lungs, the horizontal plateau is replaced by an incline, indicating that the concentration of nitrogen continues to rise during the whole expiratory phase. The significance of this will be discussed later.

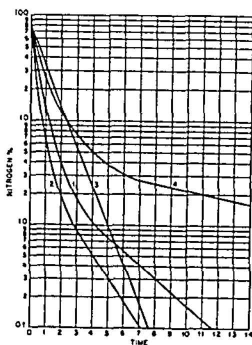
Construction of the Curve. Nitrogen concentrations of the alveolar part of each individual breath are determined from the calibration curve, tabulated, and then plotted on the ordinate of semilogarithmic paper with the time interval on the abscissa (Fig. 4-145A). A curve drawn through these points has a tail which is always a straight line.

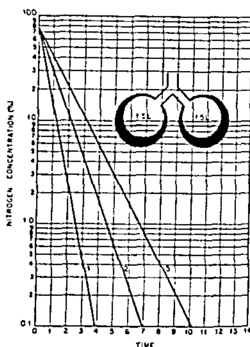
It should be stressed that accuracy of the slope of the straight end is very important and it is therefore essential to continue the washout process long enough to secure adequate data. Occasionally, the nitrogen concentration points will fit into a straight line from the beginning. The drawing of the curve through the nitrogen concentration points must necessarily be subjective. However, if the breathing is regular in depth and frequency, very little scatter is encountered and the error is small. If, on the other hand, breathing is irregular, as is frequently encountered in subjects with pathological conditions of the lung, the scatter is correspondingly larger.

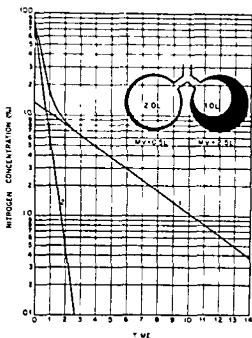
So far, no mention has been made of a correction for the small amount of measured nitrogen which was derived from the tissues and carried into the alveoli by circulating blood. The process of tissue denitrogenation has been extensively studied by Jones (1950), and it is feasible to use his denitrogenation curves for correction of clearance curves. The practical value of such corrections however remains questionable because the quantity of tissue nitrogen is relatively small and most of it is washed out during the first minutes of the clearance process. It should be borne in mind too that occasionally significant depots of nitrogen may exist in the gastrointestinal tract and even in some alveolar spaces which during normal respiration may be completely blocked off, but can be reopened by a forced cough. If such a maneuver is performed at the end of the clearance procedure, the nitrogen con-

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of the curve to t_0 (——) and read $R1_0$ on the ordinate (= 4.7). Subtract the straight line from the original curve at 0.5-min intervals, plot the differences on the corresponding ordinates, and draw a second curve (– –) through these points. Extrapolate the straight line of this curve again to t_0 and read $R2_0$ (= 25.8). Repeat the process subtracting the second straight line from the second curve, replot, and draw the third line (——). Read $R3_0$ (= 49.5). (2) Read from the graph: $t_1½ = 3.0$; $t_2½ = 0.90$; $t_3½ = 0.25$. (3) Calculate: $k_1 = 0.693/t_1½ = 0.230$; $k_2 = 0.693/t_2½ = 0.77$, $k_3 = 0.693/t_3½ = 2.772$.







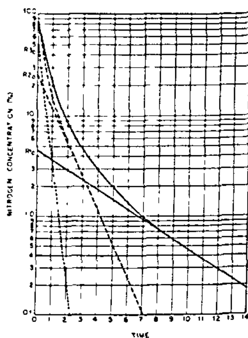


Fig. 4-145. A. General characteristics of nitrogen-clearance curves in man. (1) Normal subject. minute volume, 5.98 liters; F.R.A., 1 92 liters; R.R., 12 (2) Effect of hyperventilation on the same subject MV, 9.51 liters, R.R., 12 (3) Patient with pulmonary calcifications of undetermined origin MV, 7.0 liters; F.R.A., 3.42 liters; R.R., 15. Data fall on a straight line, indicating uniform distribution of the inspired air (4) Patient with severe emphysema and tachypnea. MV, 11.69 liters; F.R.A., 3 36 liters; R.R., 28. B. Theoretical lungs with uniform distribution Effect of minute volume on the speed of nitrogen-clearance process; lung volume, 3 0 liters. (1) MV, 5 0 liters; $t\frac{1}{2}$, 0 42 min; k, 1.66. (2) MV, 3.0 liters, $t\frac{1}{2}$, 0 693 min, k, 1.00 (3) MV, 2 0 liters; $t\frac{1}{2}$, 1.04; k, 0.666. Effect of dead space omitted. C. Theoretical lungs with uneven distribution. The lung volume is arbitrarily subdivided into $V_1 = 2.0$ liters and $V_2 = 1.0$ liters Minute volume (3.0 liters) is also arbitrarily divided into $MV_1 = 0.5$ liters and $MV_2 = 2.5$ liters. Nitrogen concentrations plotted on semilogarithmic paper against time will fit into a curve which is the sum

A point requiring comment is the fact that such pulmonary subdivisions may not be in parallel positions, since oxygen entering and leaving deeper spaces will have to pass more proximal spaces, i e, the arrangement of these spaces will be in series The general effect of such an arrangement will lead, as theoretically shown by Robertson et al, to an increase in the hypoventilated fraction of the lung, but precise quantitative determination of such an effect, or even detection of such an arrangement in man, is not possible. In the case of uniform distribution of alveolar air, dead space results in a slowing of the denitrogenation process When there is unequal distribution, the effect is unpredictable.

In view of these theoretical limitations, the empirical limits of normal variation had to be established. These represent in effect a summation of all factors mentioned. Once the limits have been established, practical application of the method is feasible and useful.

Analysis of Empirical Curves. The end part of each curve forms a straight line (Fig 4-145D) which represents the fraction of the lung with smallest turnover constant This straight line is extrapolated to t_0, and this part of the lung will then be characterized by values of k_1 and f_1. This straight line is then subtracted from the curve at 0 5-min intervals and the differences are plotted on the same graph. If the points plotted fall on a straight line, then the lungs behave in this instance as if composed of two fractions The second fraction will be characterized by f_2 and k_2 If, however, the difference points do not fall on a straight line, a curve is drawn through these points, the second straight line at the end of the curve is again extrapolated to t_0, and the second line is subtracted from the second curve, the differences are again plotted, and a third line is drawn through these points In this instance, the lungs behave as if composed of three fractions, and the third fraction is characterized by values of k_3 and f_3

CALCULATION OF VALUES OF k_1, k_2, and k_3 Absolute values for these constants can be found easily from the relationship

$$k = \frac{0.693}{t^{\frac{1}{2}}}$$

where 0 693 = natural log of 2

$t^{\frac{1}{2}}$ = half time, i e, time required for the nitrogen concentration to decrease to 50 per cent of its original value at time t_0

These half times are read directly in minutes from the graph for each straight line and the value of the constants is calculated

CALCULATION OF THE VALUES OF f_1, f_2, f_3. These fractions represent subdivisions of the lung volume and their relative sizes are expressed as decimal parts of unity. These relative sizes can be determined by integrating the area under each line. The sum of these integrals equals the area under the original curve. Definite integrals equal

$$R_{1_0}/k_1,\ R_{2_0}/k_2,\ \text{and}\ R_{3_0}/k_3$$

Then

$$f_1 = \frac{R_{1_0}/k_1}{R_{1_0}/k_1 + R_{2_0}/k_2 + R_{3_0}/k_3}$$

The values of f_2 and k_2 are calculated in a similar manner

Empirical Values of the Slow Turnover Fraction. The relative magnitude of this fraction and the numerical value of the turnover constant are probably the most sensitive indicators of abnormal distribution patterns.

In 50 experiments on 30 normal subjects with different tidal air volumes, values of k_1 lower than 0 3 were found in only three subjects (Pree and Wood). In all three instances, the corresponding lung fractions were small, amounting only to 0 12 to 0.17, i e., 12 to 17 per cent of the total lung volume The relationship of values of f_1 and k_1 to the minute volume are shown in Fig. 4-145. On the basis of these studies, patients with k_1 constants lower than 0 3 are considered abnormal The same is also true if a constant of 0 3 is associated with a fraction larger than 0 2. If the minute volume of ventilation exceeds 5 liters/m², then even values of 0 3 and 0 2 for k_1 and f_1, respectively, are abnormal

The effect of increased tidal volume upon the magnitude of f_1 and k_1 has been studied by the author in a series of carefully controlled paired experiments on 23 subjects An increase in tidal volume invariably increased the value of k_1, although this increase was not proportional to the changes in tidal volume The corresponding f_1 also changed, but no definite pattern in these changes could be established

Effective Coefficient of Ventilation (K) of Robertson, Siri, and Jones. The average turnover constant for a whole lung with several subdivisions (f_1, f_2, f_3) was calculated by these authors from the equation

$$\frac{1}{K} = \frac{f_1}{k_1} + \frac{f_2}{k_2} + \frac{f_3}{k_3}$$

and was expressed as the effective coefficient of ventilation The values for this coefficient show consistent change with changes in the values of

centration will sharply rise, sometimes by several per cent, and after a few breaths it will again return to a low level.

A clearance curve constructed in this way is of the exponential type and can be resolved into two, or at most three, components. The interpretation of these components will ultimately depend upon several theoretical and empirical considerations. It therefore seems convenient to deal with these considerations first and then continue with the practical analysis of the curve.

THEORY

Mechanical ventilation has been conventionally described as a cyclic process which can be illustrated well by a single bellows (Fig 4-145B). If V is the volume of the lung at the point of normal expiration (*FRC*) and T is the tidal volume, then, if pure oxygen is breathed in beginning at time t, the amount of nitrogen originally present in the lungs (Q_0) will undergo serial dilution and the speed of the dilution will depend upon the ratio of the two volumes V and $(V + T)$. The quantity of nitrogen remaining in the lung at any time during the nitrogen washout process can be expressed by a simple equation

$$Q = Q_0 \left(\frac{V}{V + T}\right)^{nt} \qquad (1)$$

where n = the respiratory rate, in cycles per minute

This concept has been applied to nitrogen dilution curves by Fowler et al. in an attempt to differentiate the effect of increased dead space and of unequal ventilation.

There has been increasing experimental evidence that the cyclic character of ventilation at the alveolar level is lost because of diffusion around the concentration boundary, asynchronism of inspiratory and expiratory phases in different parts of the lungs, and other factors One is therefore justified in considering the alveolar ventilation as a continuous process, bearing in mind that both this and the cyclic concepts are only approximations of reality and that, in each individual instance, the lung may be approximated better by one or the other. The second concept of alveolar denitrogenation as a continuous process was developed by Robertson et al, who applied the tissue denitrogenation theory of Jones to alveolar ventilation. Their theory has been followed in the author's laboratory, partly because of serious theoretical objections to the strictly cyclic concept, and partly because in practice it is often impossible to obtain uniform tidal volumes in subjects with pulmonary disease.

According to Jones, the above equation can be rewritten in the form

$$Q = Q_0 e^{-kt} \qquad (2)$$

where k = ratio of minute volume to lung volume (nT/V)

e = the base of the natural logarithms

The rate of denitrogenation dQ/dt has been expressed by these authors as R, so that the final form of the equation becomes:

$$R = R_0 e^{-kt} \qquad (3)$$

If alveolar denitrogenation were strictly a cyclic process, then Eq (3) would become

$$R = R_0 e^{-nt \ln(V/V+T)} \qquad (4)$$

In either instance the values for R plotted against time on semilogarithmic paper will give a straight line.

Consider now a situation where the alveolar ventilation of the lungs is not uniform and assume that the lung consists of two subdivisions (f_1, f_2) connected in parallel (Fig. 4-145C). Then the minute volume nT will also be subdivided, independently of the size of f_1 and f_2, into nT_1 and nT_2 The rate of denitrogenation of each subdivision will depend again upon their turnover constants,

$$k_1 = f_1/nT_1 \qquad \text{and} \qquad k_2 = f_2/nT_2$$

The smaller the constant, the longer will be the time required to complete the denitrogenation of the corresponding subdivision The denitrogenation process of the whole lung can then be expressed as the sum of these two denitrogenation rates

$$R = R_{1_0} e^{-k_1 t} + R_{2_0} e^{-k_2 t} \qquad (5)$$

Although in reality the denitrogenation of individual alveoli in human lungs proceeds with a number of different speeds, the lungs behave, when the nitrogen clearance method is used, as if they are composed of only two or at most three subdivisions of different sizes, and as if the alveoli within each of the subdivisions are ventilated with identical speed If the values for R_1, R_2, and R_3, are plotted against time on semilogarithmic graph paper, three straight lines of different slopes will be obtained but the plot for the whole lung (R) will be a curve, which can be easily resolved into its components

10

Tracings of the venous system and from thoracic organs

Jugular Tracings
DAVID GELFAND

Tracings of the Pulsations of the Liver (Hepatic Tracings)
ALDO A. LUISADA

Pneumocardiography
ALDO A. LUISADA

Esophagocardiography
VITTORIO PUDDU AND LUIGI CARDI

JUGULAR TRACINGS

HISTORY

References to pulsations of the veins in human beings can be found in the writings of Lancisi (1740) and Morgagni (1762). The first recorded phlebograms were made by Wedemeyer (1828) on dogs In 1865, Friedreich recorded human venous tracings, followed by Potain (1867), who recorded a venous tracing from his own neck and from that of his sister. Many distinguished investigators recorded and analyzed the venous pulse; however, MacKenzie initiated a clinical and physiological evaluation of the jugular tracing Later work in this field was done by Wenckebach and Lewis

Because of advances in electrocardiography and the identification of arrhythmias by this method, few recordings of the jugular tracing were made for a number of years More recently, the studies of Houssay, Caeiro, Groedel, and Luisada have served to emphasize the importance of this technical study and to increase the interest of many investigators.

Originally, jugular tracings were recorded by *sphygmographic methods.* A funnel was lightly applied over the bulb of the right jugular vein and by means of a rubber tube and air transmission with a Marey tambour, the waves of the jugular pulse were recorded on smoked paper *Optical-photographic recording* of the jugular pulse was first obtained by mechanical-optical transmission, e g., lever to mirror, or funnel to a Frank's or a Wigger-Dean capsule The first machine to use *electrical transmission* for phlebography was the Bock-Thoma apparatus Here the lever system was replaced by a microphone for recording At present, a double-rim suction chest piece connected to a crystal (piezoelectric) microphone which has a linear response has replaced other equipment in most laboratories

TECHNIQUE

The best site for recording the jugular pulse is the right jugular bulb, however, good records may be obtained from the entire jugular vein if the venous pressure is elevated The patient is in the supine position and the tracing is recorded with the breath held in an intermediate respira-

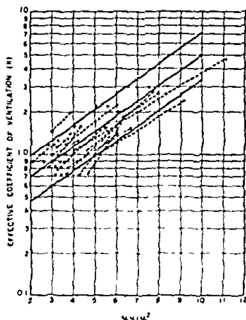


Fig. 4-146. Correlation of the effective coefficient of ventilation (K) and minute volume per square meter; (————) paired experiments and (·) single experiments in normal subjects.

minute volume. This relationship has been established from a series of paired experiments (Fig 4-146). The value of this correlation lies primarily in eliminating seemingly normal coefficients. To illustrate this point, the value K = 1 0 would be perfectly normal for a minute ventilation of 3 liters/m² BSA but would be abnormally low for a ventilation of 6 liters/m² Furthermore, this correlation can also be used in repeated determinations in the same subject when the minute volumes during these tests are different.

Significance of the Alveolar Slope. The type of curve illustrated in Fig 4-145 cannot develop as a result of multiple subdivisions of the lung if these subdivisions are arranged in parallel, and inspiratory and expiratory movements in these subdivisions proceed exactly in phase. If there is asynchronism of the ventilatory phases in individual fractions of the lung, however, this type of curve will be observed. Such asynchronism has been experimentally produced by Fowler et al. by introduction of resistance into air passages This type of curve has been used for the single breath test of uneven distribution. The subject inspires a single breath of pure oxygen and then expires slowly through a flowmeter while the sampling needle is inserted into tubing as previously described. A time point is determined on the flow curve when the volume of expired air reaches 750 ml, and the instantaneous nitrogen concentration at this point is determined from the nitrogen curve. Another point is determined when the volume of expired air reaches 1,250 ml, and the nitrogen concentration is read again. In normal subjects, the difference between the nitrogen concentrations at these two points does not exceed 2 per cent. In abnormal subjects, the difference is roughly proportional to the degree of unevenness of distribution This test is simple and eliminates time-consuming measurements and analyses of the continuous clearance curve, on the other hand, it does not give such thorough insight into the distribution process as does the continuous clearance test method.

Distribution patterns in patients with heart disease and with degenerative diseases of the lungs will be discussed in a subsequent chapter.

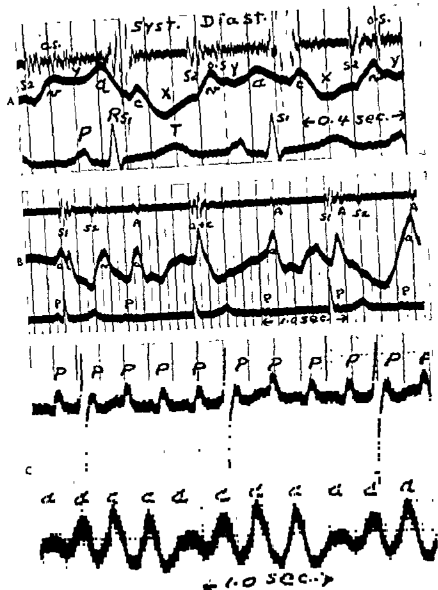


Fig. 4-147 A Normal jugular tracing from a patient with rheumatic mitral stenosis Note that the positive A, C, and V waves and the negative X and Y waves are easily identified The tracing is smooth throughout, except for a notch between the A and C waves (transmission of tricuspid valve closure) and a notch on the proximal limb of the V wave (closure of the semilunar valves). With relation to the electrocardiogram and the cardiac cycle, the A wave is presystolic, the C wave is early systolic, the X wave is systolic, the V wave is early diastolic, and the Y wave is diastolic. B. Tracing from a patient with complete AV heart block Each P wave in the electrocardiogram is followed by an atrial sound in the phonocardiogram and a positive A wave in the jugular tracing In beat 2 the A and C waves coincide, giving rise to a single, large, peaked wave Note the increase in intensity of the 1st heart sound (beat 1) when the P-R interval is short C Tracing from a patient with 4·1 atrial flutter. Note a positive A wave follows each flutter wave in the electrocardiogram.

tory position. In order to obtain a good tracing, the venous pressure must be greater than the atmospheric pressure. Hence, in normal subjects it may be necessary to position the jugular bulb slightly below the level of the right atrium. This is accomplished either by raising the body or by lowering the head. In patients with an elevated venous pressure, a semirecumbent or even a sitting position may be satisfactory.

The *chest piece* is a double-rim cup. The outer chamber is connected to a rubber bulb which, when squeezed, holds the chest piece lightly to the jugular bulb by means of suction. The inner chamber is connected to the piezoelectric transducer by a short rubber tube The air pressure changes set up in the applicator cup by the venous pulse are transmitted to the piezoelectric transducer. This converts them into equivalent, minute, electrical pulsations which are then fed into the electrocardiographic amplifier and recorded like an electrocardiogram. Tracings recorded by this method are accurate and reliable, since the recording instrument has an over-all natural frequency higher than 100/sec

THE NORMAL JUGULAR TRACING

The normal jugular tracing has *three positive waves* (A, C, and V) and *two negative waves* (X and Y) (Fig 4-147A) Since this is a closed system filled with blood, the waves are principally the result of volume changes. However, changes in pressure and velocity may, under certain conditions, be factors in the production of the waves

The A wave is positive It is the result of atrial contraction which causes the blood flow to that chamber to stop. A recoil (or tidal wave) is set up in the jugular vein and is recorded as the positive A wave. With normal sinus rhythm, the A wave is presystolic in time In AV block (Fig. 4-147B), the A wave can appear in any part of the cardiac cycle and, in atrial flutter (Fig. 4-147C), more A waves are present than any other waves of the jugular pulse With atrial fibrillation (Fig 4-148A), the A wave is absent, because the fibrillary contractions of the atrium are too small to be recorded in the jugular tracing Normally, the A wave is gently rounded, and has a moderate amplitude, greater than that of the C wave and about the same as that of the V wave

The C wave is positive, occurring early in systole just after the opening of the semilunar valves. MacKenzie designated it with the letter C because he felt that it was caused by the transmission of the carotid pulse. However, the C wave appears even when the carotid artery is pinched off. The most common explanation for the C wave is that it is the result of a double phenomenon: first a bulging of the tricuspid valve into the right atrium during the tension period; then a pulsation transmitted from the ascending aorta to the superior vena cava during early ejection. The latter is absent in tracings recorded from the inferior vena cava of animals. Normally the C wave is small in amplitude and appears to simply interrupt the systolic collapse (X) of the jugular pulse.

The V wave is positive. This wave is the result of blood collecting in the right atrium while the tricuspid valve is closed. As the volume of blood increases in the atrium, the V wave increases in amplitude until it reaches its peak in early diastole, when the tricuspid valve opens. Essentially this is a stasis wave and is principally dependent on changes in volume in the right atrium.

The X wave (*systolic collapse wave*) is negative It is the result of the AV septum being drawn down during the maximal ejection phase of ventricular systole while the right atrium is being filled with blood.

The Y wave (*diastolic collapse wave*) is negative. It is the result of the emptying of the right atrium into the right ventricle. This is terminated by the filling of the right atrium and the subsequent A wave.

It must be remembered that the jugular pulse mirrors mechanical events which occur in the right side of the heart, hence it may have no constant relationship to the electrocardiogram (except for the A wave, which follows each P wave) Events occurring in the two ventricles may have a slight asynchronism This may become greater in pathological conditions

The hepatic tracing mirrors the jugular tracing except that, in the former, the C wave is small or absent (see above)

The A wave is related to the 4th (atrial) heart sound, the peak of the A wave appearing shortly after this sound The 1st cardiac sound complex interrupts the systolic (X) collapse and precedes the C wave. The 2d heart sound precedes the peak of the V wave by 0.10 to 0 11 sec The 3d heart sound usually appears on the descending limb of the V wave at the beginning of the diastolic (Y) collapse.

phenomenon in approximately one-third of his patients with this condition) The second A wave appears on the downstroke of the initial A wave. It is the result of a later contraction of, and, in early stages of this condition, a higher pressure in the left atrium as compared to the right atrium The late increase in volume in the right atrium is transmitted to the jugular vein and appears as a second A wave. This phenomenon disappears with atrial fibrillation or when the right atrial pressure equals or exceeds the left atrial pressure. The Valsalva maneuver, by increasing the pressure in the right atrium, reduces or stops the left-to-right shunt of blood. The double A wave is replaced by a single, tall, and peaked A wave (compare with the A wave of pulmonary hypertension) with some ventricularization of the systolic jugular pulse. When the Valsalva maneuver is discontinued the double A waves reappear.

Interventricular Septal Defect (Congenital and Acquired). Normally the jugular tracing

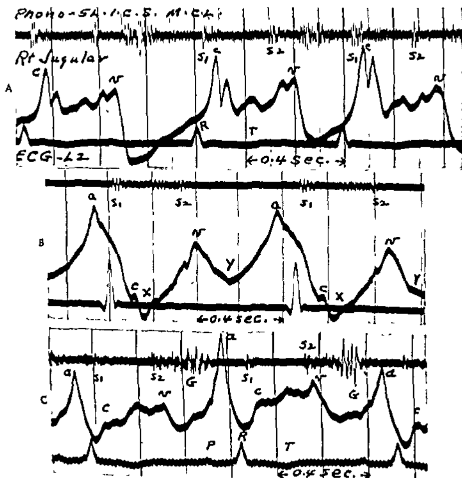


Fig. 4-148. A Tracing from a patient with mitral stenosis and atrial fibrillation. Note the absence of P waves in the electrocardiogram. The systolic (X) collapse has been replaced by a positive systolic wave with a late rise to the peak of the V wave, the diastolic (Y) collapse is not affected. This finding is indicative of marked tricuspid insufficiency B Tracing from a patient with congenital pulmonary valvular stenosis (right ventricular pressure 98/30) The A waves are tall and peaked particularly in relation to the amplitude of the C wave and the V wave. C. Tracing from a patient with syphilitic aortic insufficiency complicated by left and right heart failure The A waves are tall and peaked and are characteristic of the increased venous pressure found in congestive heart failure The systolic plateau with a late rise is indicative of severe relative tricuspid insufficiency.

ARRHYTHMIAS

The jugular pulse is of definite value in *atrial arrhythmias* since coordinated right atrial contraction is reflected in the tracing by positive A waves (Fig. 4-147C) In *atrial tachycardia* with 2:1 heart block, one of the P waves may be buried in the QRS complex and cannot be readily identified; in such instances the demonstration of A waves in the jugular tracing will help to establish the diagnosis. The same is true of *atrial flutter* with 2:1 heart block. At times flutter waves in the electrocardiogram cannot be distinguished from atrial fibrillation with coarse fibrillatory waves; in such cases the demonstration of regular A waves in the jugular tracing will establish the differential diagnosis.

In *nodal rhythm* (particularly mid- or low-nodal), the retrograde P wave may be difficult or impossible to identify in the electrocardiogram. In such cases the demonstration of A waves in the jugular tracing will be useful in diagnosis

In differentiating between ventricular tachycardia and supraventricular tachycardia with aberration, the demonstration of positive A waves, usually at half the ventricular rate, in the jugular tracing will be most helpful

BUNDLE BRANCH BLOCK

The A wave is not affected by either right or left bundle branch block

The C wave has an inconstant relationship and may be delayed in appearance in left bundle branch block with no change in timing in right bundle branch block

The most constant change is in the timing of the V wave In *left* bundle branch block, the peak of the V wave comes between the two phases of the 2d heart sound while the time interval between the 2d and 3d heart sounds is increased. In *right* bundle branch block, the peak of the V wave is delayed, coming after the second phase of the 2d heart sound, the time interval between the 2d and 3d heart sounds being shortened.

VALVULAR LESIONS

Since the jugular pulse records right heart events, malfunction of the tricuspid valve may be demonstrated by a jugular tracing. With *tricuspid insufficiency* (Fig. 4-148A) there is ventricularization of the jugular pulse The systolic (X) collapse is replaced by a positive, systolic wave. In severe lesions, the systolic rise occurs early and the curve shows a *systolic plateau* which resembles an intraventricular pressure curve.

If sinus rhythm is preserved in the presence of *tricuspid stenosis,* the finding of *tall, peaked atrial waves* may be of little diagnostic value since these can be caused by either right ventricular hypertension or heart failure. It has been the author's experience, however, that patients with organic tricuspid stenosis have an advanced form of heart disease and the mechanism is that of atrial fibrillation in the great majority of cases. In such patients, the demonstration of a regular, positive, systolic pulsation (Fig. 4-148A) in the jugular tracing is of great diagnostic value.

HYPERTENSION OF THE LESSER CIRCULATION: CONGESTIVE HEART FAILURE

With hypertension of the lesser circulation, as in *congenital heart disease* (pulmonary valvular stenosis) or in *chronic cor pulmonale* (emphysema), there is increased pressure in the right atrium which is reflected in the jugular tracing by a *tall, peaked, presystolic atrial wave* (Fig. 4-148B). If the right heart fails, a relative tricuspid insufficiency is manifested by a systolic plateau.

Figure 4-148C illustrates the jugular tracing from a patient with right and left heart failure and markedly increased venous pressure. In such patients there is a marked prominence and peaking of the presystolic atrial wave The positive, systolic pulse with its early rise is evidence of severe tricuspid insufficiency.

SEPTAL DEFECTS

Interatrial Septal Defect. The presystolic atrial wave of the jugular pulse is dependent upon right atrial contraction with resulting changes in volume, pressure, and velocity in the jugular vein In the presence of an interatrial septal defect, with sinus rhythm and coordinated atrial contraction, the shunt of blood from the left to the right atrium may cause *a double A wave* to appear (Fig 4-149A) in the jugular tracing (Luisada has observed this

TRACINGS OF THE PULSATIONS OF THE LIVER (HEPATIC TRACINGS)

The hepatic tracing is recorded without difficulty when the liver is enlarged or lowered; tracings of normal individuals are obtained less readily.

HISTORY

The hepatic tracing was first studied many years ago (Potain, MacKenzie). The importance of this record is due to the facts that (1) the liver is influenced by changes of flow and pressure in the inferior vena cava, and (2) there is no underlying arterial vessel (corresponding to the carotid artery under the jugular vein) which may affect the record

TECHNIQUE

Older records were obtained by means of a Marey tambour or a Frank's capsule. Modern procedure is based on the fact that a crystal microphone of linear type transforms pulsations of the air contained in the applicator into electrical waves These are recorded by the galvanometer of an electrocardiograph and are transcribed photographically or by direct-writing methods Another sound or mechanical tracing should be simultaneously re- [illegible]

tween the crystal microphone and the galvanometer The sensitivity of the linear microphone is such that the round bell normally used for taking low-frequency tracings of the chest (Part 3, Chap 9) is sufficient for recording hepatic tracings Another microphone, connected to the cup as a support, is placed over the right upper quadrant of the abdomen and is held by a rubber strap If respiration is forceful and irregular, the micro-

phone In normal individuals, the same procedure may be used on that part of the liver which crosses the epigastrium by firmly applying the cup below the right costal arch Respiratory movements possess an amplitude far greater than the hepatic waves, therefore, it is necessary for the patient to hold his breath for a few seconds during the time the tracing is being taken. If the patient is unable to do so, closing the *nose and mouth* by hand for a few *seconds may* be necessary Otherwise, a high-pass electric filter may be used This reduces the amplitude of all slow waves, so that the shape of certain hepatic waves is somewhat changed. Detection of a plateau might be more difficult with the use of a filter.

ANALYSIS OF THE WAVES

The hepatic tracing shows a small positive wave during presystole (*A wave*) (Fig. 4-150). It is due to presystolic swelling of the liver when atrial contraction arrests the venous inflow. Regurgitation of blood in presystole is minimal in normal individuals while it may be important in subjects with high venous pressure The A wave of the jugular tracing and that of the hepatic tracing are practically simultaneous However, the jugular A wave may precede the hepatic A wave, especially if the former is recorded through an amplifier. The rise of the A wave of the hepatic tracing precedes the 1st heart sound at the apex by about 0 15 sec. Tracings of patients who have high venous pressure and distended livers may present atrial waves which are much higher in the hepatic than in the epigastric tracing, proving the hepatic origin of this wave. In exceptional cases, a *double presystolic wave* may be recorded The first (A) is transmitted through the diaphragm via the epigastrium; the second (A') is a real hepatic wave, and takes place somewhat later

The beginning of ventricular contraction is revealed by a small, positive wave (*AV wave*), possibly transmitted through the diaphragm and coinciding with tricuspid valve closure.

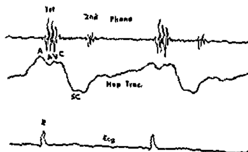


Fig 4-150 Hepatic tracing of a normal individual compared with the phonocardiogram (Phono) and the electrocardiogram (Ecg) SC indicates systolic collapse.

has a smooth contour (Fig. 4-147A) with no serrations between the positive A, C, and V waves, and the negative X and Y waves. The presence of murmurs in systole, diastole, or both is not transmitted to the jugular tracing. Figure 4-149B shows the tracing from a patient with congenital interventricular septal defects. In the jugular tracing of this patient, note that between the C and V waves there are serrations and undulations which begin at the same time that the late, crescendo systolic murmur is inscribed, and which end with the 2d heart sound before the peak of the V wave. The jugular tracing, aside from these serrations and undulations, is smooth. Laubry and Pezzi (1913) reported five patients with congenital heart disease with an interventricular communication in whom the fine undulations between the C and V waves were "ascribed to a carotid origin and . . . attributed to the thrill engendered by the perforation of the septum and propagated from the aorta to the vessels of the neck" It is the author's opinion that they are caused by the "late" shunt of blood from the left to the right ventricle during ventricular systole. The shunt strikes the septal leaflet of the tricuspid valve, setting up vibrations that are transmitted to the jugular vein (in some instances there is a direct shunt from the left ventricle to the right atrium). This diagnostic sign has been most helpful in the diagnosis of defects resulting from rupture of the septum following myocardial infarction, acute or subacute bacterial endocarditis, and (in one patient) a stab wound.

MISCELLANEOUS CONDITIONS

The jugular tracing may be helpful in demonstrating coordinated atrial contraction, by the presence of presystolic atrial waves, in beriberi heart disease, hypothyroidism, anasarca, or acute and chronic pericardial disease, in which the voltage of the P waves in the electrocardiogram may be quite low.

CONCLUSIONS

The jugular tracing is of value in diagnosing (1) arrhythmias, (2) valvular defects, chiefly of the tricuspid valve, (3) hypertension of the lesser circulation and heart failure, (4) bundle branch block, (5) septal defects (interatrial and interventricular), and (6) conditions characterized by low voltage of the P wave in the electrocardiogram

It is a simple, rapid, nontraumatic diagnostic procedure that may be extremely helpful in differential diagnosis.

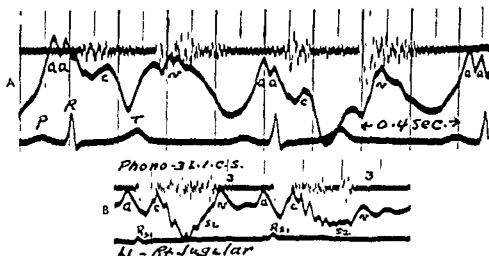


Fig. 4-149. A Tracing from a patient with interatrial septal defect A double A wave is present in presystole, the second appearing well before the QRS complex of the electrocardiogram The other waves in the jugular pulse are unaffected and are normal in appearance. B. Tracing from a patient with congenital interventricular septal defect There are serrations and undulations between the C wave and the V wave; these appear at the same time as the late, crescendo systolic murmur is inscribed in the phonocardiogram. The rest of the jugular tracing is unaffected and remains a smooth trace.

PNEUMOCARDIOGRAPHY

The term "internal pneumocardiogram" is now applied to the tracing of the pulsations of the air passages and lungs which are a consequence of the heart beat. Previous terms were "negative thoracic pulse," "cardiopneumatic waves," "respiratory pulse," and "heart notchings of the respiratory curve."

HISTORY

Older studies showed that the heart beat causes changes of pressure within the thorax, and movements of air through the respiratory passages In heart disease, these movements may increase in such a way that the observer becomes aware of them, and there may even be a subjective sensation. The first clinical observations were made between 1667 and 1888 by Friedreich, Galvagni, and Cheesmann, more recently, Fischer (1903) and Lang (1912) published clinical studies

Pressure Curves. Buisson studied the so-called negative thoracic pulse in animals and explained it with the decrease in volume of the heart resulting from ventricular systole. Bert studied the pulsations of air of the trachea due to the movements of the heart. Landois obtained records of air pulsa- [illegible] diminution of pressure within the chest. Klewitz (1918) described the pneumocardiogram in detail He noted a small negative wave during presystole and a larger one during systole Small notches coincided with the two heart sounds

Pneumotachograms. A third phase started with the description of the pneumotachograph. This apparatus records a tracing of the velocity of the air flow during normal respiration The "cardiac notches" of the pneumotachogram were studied by Luisada (1928) in normal subjects and cardiac patients, and were compared with those of the pressure curve. They were found basically identical Actual backflow of air was found only during apnea Three main negative waves were described presystolic, systolic, and diastolic A high positive pulse sometimes occurred in an untrained patient asked to hold his breath, because he also closed his glottis Later studies by Holzloehner were mostly based on the use of a pneumotachograph and a string anemometer

Another technique was described by Luisada (1942), who used a crystal microphone, a high-pass filter, and a galvanometer Subsequent studies were made by Groedel.

TECHNIQUE

A photographic or direct-writing galvanometer is used for the simultaneous registration of the pneumocardiogram and a phonocardiogram (this is necessary for timing the waves of the former) A *crystal microphone* of the linear type is used in conjunction with a *high-pass filter*, which decreases the slow respiratory deflections of the base line without curtailing the rapid pulsations caused by the heart The jack of the linear microphone is inserted into the filter, that of the filter, into the electrocardiograph The filter can be varied in the degree of attenuation of the slow respiratory deflections. A 10-in. rubber tube, connected to the microphone, ends in an olive of bakelite inserted into one of the patient's nostrils The patient is placed in a comfortable sitting or semirecumbent position, with complete muscular relaxation, and is instructed to breathe through the nose with his mouth closed.

Two operating adjustments can be made. the degree of filter attenuation upon slow respiratory waves and the amplification of the galvanometer. Regulation of both gives a tracing having waves from 1 to 2 cm high, while even the extreme phases of respiration are recorded. The pneumocardiogram is registered at a film speed of 50 to 100 mm/sec If the patient is able to breathe evenly and slowly, the filter may be omitted and the accuracy of the tracing is increased The electrical filter does not remove completely the low-frequency components caused by respiration. Thus, some waves may be seen in one cycle and not in a succeeding one, because of the dissimilar rhythms of respiration and cardiac action These respiratory components are more marked in children and excitable adults Pneumocardiographic waves may be differentiated from respiratory waves because they occur in every succeeding cardiac cycle, although somewhat modified in contour

ANALYSIS OF WAVES

It has been proved that the waves of the internal pneumocardiogram mirror the changes in intrathoracic pressure Apart from respiratory actions, the latter are affected chiefly by the balance between the flow of blood from and into the thorax. Rapid outflow not compensated by inflow (or arrest of inflow while the outflow continues) causes a suction effect which is compensated by inflow of air and is revealed by a negative wave in the pressure

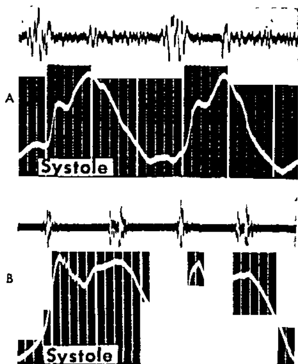


Fig. 4-151. Hepatic tracings of two cases of rheumatic heart disease with mitral stenosis and tricuspid insufficiency and stenosis. Phonocardiograms simultaneously recorded for timing Instead of the systolic collapse, there is a systolic plateau, evidence of tricuspid regurgitation. This plateau has a slower rise in the upper tracing (A), organic lesion, and a more rapid rise in the tracing below (B), relative insufficiency. (From Luisada Heart Beat Hoeber, 1953)

Following this, there is a deep *systolic collapse* In normal individuals, the collapse recorded *below the right costal arch is far deeper than* that recorded below the left costal arch Therefore, the former is the result of *decreased hepatic volume* while the latter is due to the rise of the diaphragm followed by a decrease of abdominal pressure Sometimes, a small notch can be seen during that part of the 1st heart sound which coincides with the opening of the *semilunar valves and during the wave 1b of* the cardiogram; it is probably transmitted through the diaphragm, and should be called *C wave*

The tracing rises gradually at first, rapidly later, *with a peak (V wave) at the time of* the opening of the tricuspid valve. Following this, the curve falls, forming a deep and rounded negative wave *(diastolic collapse)* which varies in shape and depth because of the effect of respiration on venous return. The lowest point of this wave coincides with the wave of rapid filling of the cardiogram, so that this collapse may also be called wave 3 (3d sound).

It should be kept in mind that, if there is enlargment of the right heart, a right ventricular impact may be transmitted through the diaphragm. It will be transcribed as an early-systolic wave followed by a deep depression.

CLINICAL STUDIES

The hepatic tracing has been studied in diseases of the tricuspid valve by MacKenzie, Kerr and Warren, White and Cooke, Hallock and Clarke, Groedel, Luisada, and Messer et al.

The tracing characteristic of *tricuspid insufficiency* shows *a high positive presystolic wave* (unless atrial fibrillation is present), and *a high, positive, systolic wave.* The latter assumes in severe lesions the aspect of a positive, *systolic plateau,* similar to a tracing of intraventricular pressure (Fig. 4-151). Associated stenosis causes a delay in both the rise and the fall of the tracing. This would differentiate insufficiency due to valvulitis from that due to dilatation (Messer et al), usually of functional nature If the regurgitation is moderate, the wave is more rounded, has a slow rise, a peak in late systole, and an abruptly descending limb in early diastole. Patients yielding such a hepatic tracing are said to have a "systolic liver"

In *tricuspid stenosis,* the hepatic tracing shows *a high presystolic* wave if sinus rhythm is preserved This large wave has no diagnostic value because it may be present in patients having heart failure and right ventricular hypertension without tricuspid stenosis (Grishman et al).

In constrictive pericarditis, the hepatic waves are usually small and difficult to record. An inspiratory rise of the tracing (swelling of the liver. *Kussmaul's sign*) may be recorded. The constrictive process tends to limit the transmission of the waves caused by cardiac dynamics, therefore, possible abnormal waves are *not* due to the adhesive process per se; on the contrary, they are decreased in amplitude by it.

PNEUMOCARDIOGRAPHY

The term "internal pneumocardiogram" is now applied to the tracing of the pulsations of the air passages and lungs which are a consequence of the heart beat Previous terms were "negative thoracic pulse," "cardiopneumatic waves," "respiratory pulse," and "heart notchings of the respiratory curve."

HISTORY

Older studies showed that the heart beat causes changes of pressure within the thorax, and movements of air through the respiratory passages In heart disease, these movements may increase in such a way that the observer becomes aware of them, and there may even be a subjective sensation. The first clinical observations were made between 1867 and 1888 by Friedreich, Galvagni, and Cheesmann, more recently, Fischer (1903) and Lang (1912) published clinical studies

Pressure Curves. Buisson studied the so-called negative thoracic pulse in animals and explained it with the decrease in volume of the heart resulting from ventricular systole. Bert studied the pulsations of air of the trachea due to the movements of the heart Landois obtained records of air pulsations from the mouths of normal subjects. Mosso recorded the same tracing and described a double-notched wave due to systolic diminution of pressure within the chest. Klewitz (1918) described the pneumocardiogram in detail. He noted a small negative wave during presystole and a larger one during systole Small notches coincided with the two heart sounds

Pneumotachograms. A third phase started with the description of the pneumotachograph This apparatus records a tracing of the velocity of the air flow during normal respiration The "cardiac notches" of the pneumotachogram were studied by Luisada (1928) in normal subjects and cardiac patients, and were compared with those of the pressure curve. They were found basically identical Actual backflow of air was found only during apnea. Three main negative waves were described presystolic, systolic, and diastolic A high positive pulse sometimes occurred in an untrained patient asked to hold his breath, because he also closed his glottis. Later studies by Holzlochner were mostly based on the use of a pneumotachograph and a string anemometer.

Another technique was described by Luisada (1942), who used a crystal microphone, a high-pass filter, and a galvanometer. Subsequent studies were made by Groedel.

TECHNIQUE

A photographic or direct-writing galvanometer is used for the simultaneous registration of the pneumocardiogram and a phonocardiogram (this is necessary for timing the waves of the former). A *crystal microphone* of the linear type is used in conjunction with a *high-pass filter,* which decreases the slow respiratory deflections of the base line without curtailing the rapid pulsations caused by the heart. The jack of the linear microphone is inserted into the filter, that of the filter, into the electrocardiograph The filter can be varied in the degree of attenuation of the slow respiratory deflections A 10-in rubber tube, connected to the microphone, ends in an olive of bakelite inserted into one of the patient's nostrils The patient is placed in a comfortable sitting or semirecumbent position, with complete muscular relaxation, and is instructed to breathe through the nose with his mouth closed.

Two operating adjustments can be made. the degree of filter attenuation upon slow respiratory waves and the amplification of the galvanometer. Regulation of both gives a tracing having waves from 1 to 2 cm high, while even the extreme phases of respiration are recorded. The pneumocardiogram is registered at a film speed of 50 to 100 mm/sec. If the patient is able to breathe evenly and slowly, the filter may be omitted and the accuracy of the tracing is increased. The electrical filter does not remove completely the low-frequency components caused by respiration. Thus, some waves may be seen in one cycle and not in a succeeding one, because of the dissimilar rhythms of respiration and cardiac action. These respiratory components are more marked in children and excitable adults Pneumocardiographic waves may be differentiated from respiratory waves because they occur in every succeeding cardiac cycle, although somewhat modified in contour

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It has been proved that the waves of the internal pneumocardiogram mirror the changes in intrathoracic pressure Apart from respiratory actions, the latter are affected chiefly by the balance between the flow of blood from and into the thorax Rapid outflow not compensated by inflow (or arrest of inflow while the outflow continues) causes a suction effect which is compensated by inflow of air and is revealed by a negative wave in the pressure

tracing. Acceleration of inflow of blood into the chest without equivalent increase of outflow causes a pressure effect which is compensated by outflow of air and is revealed by a positive wave in the pressure tracing. The movements of two valves, the tricuspid valve on the one hand and the aortic valve on the other, are the most important because they regulate venous flow into the chest, and arterial flow from it. The normal pneumocardiogram presents *five negative waves*, each connected with certain phases of cardiac action, and several small positive connecting points which may become *positive waves* (Figs. 4-152; 4-153).

During *presystole*, a negative wave is present in the pneumocardiogram. It is due to the arrest of venous flow (or backflow into the large veins) caused by the contraction of the right atrium and should be called A wave. This results in suction of air into the chest.

A small positive wave occurs before the jugular tracing reaches the bottom between the A and C waves. Lowering of the tricuspid leaflets by the papillary muscles creates a slight aspiration of blood causing outflow of air from the chest. This wave is called P_1 (papillary contraction, first positive wave, Fig. 4-153).

During the first half of *systole*, the blood leaves the thorax through the branches of the aortic arch and the abdominal aorta. At the

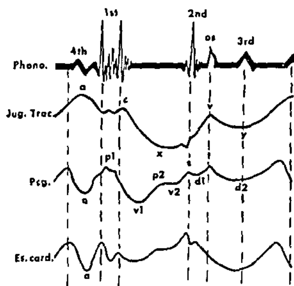


Fig. 4-152. Scheme of the pneumocardiog am (Pcg) and the time relationship of its waves with those of the sound tracing (Phono), jugular tracing (Jug Trac) and esophagocardiogram (Es card). (From Luisada. Heart Beat. Hoeber, 1953.)

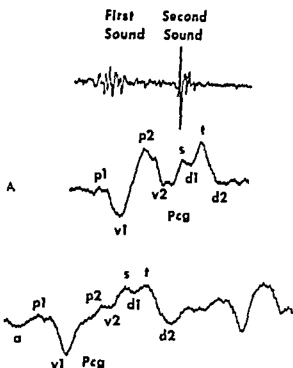


Fig. 4-153. Pneumocardiograms (Pcg) and phonocardiogram (above) of normal subjects. Tracing (A) was recorded simultaneously with the phonocardiogram (above).

same time, the venous blood either moves slowly toward the right atrium (inferior vena cava), or has a short backflow (superior vena cava—C wave of the jugular tracing). In this phase, considerable aspiration of air into the thorax takes place and an important depression is present in the pneumocardiogram. This wave is often the most marked of all, and is called V_1 (first ventricular wave).

After the first part of systole, pronounced aspiration is exerted on the veins by increased negative pressure in the thorax and lowering of the floor of the right atrium. This causes acceleration of the venous flow from both venae cavae, as shown by the jugular and hepatic tracings. The pneumocardiogram shows an upright notch which normally does not reach the zero line but in some cases may become a positive wave. The pulsations of the pulmonary arteries [1] and those of the tracheal

[1] Theoretically, the pulsation of the pulmonary vessels should not produce changes in the pneumocardiogram because the movement of blood is intrathoracic. However, the contact between small arteries of the lungs and alveolar air is so intimate that the decreased volume of the right ventricle has more effect on the venous flow, while the increased volume of the lungs has a greater effect on the flow of air.

and nasopharyngeal vessels may contribute to the formation of *this wave. This wave is called* P_2 (peripheral pulse, second positive wave).

During the second half of systole, venous flow is slow because the right atrium is nearly filled while arterial flow from the aortic arch continues. This causes suction of air into the chest and a negative wave. This wave, called V_2 (second ventricular wave), may be deeper than V_1

An upright notch is simultaneous with the 2d sound and the *incisura* of the carotid tracing. *This is called S (semilunar valve closure)* During the isometric relaxation period, a straight line or a small downward wave is present The latter is called D_1 (first diastolic wave). Opening of the tricuspid valve causes a sudden influx of blood from the venoatrial reservoir into the right ventricle and accelerates the venous flow The moment of opening is marked by an upright notch called *T* (tricuspid opening). It occurs simultaneously with the lowest point of the apex cardiogram (point o) and *coincides with, or slightly precedes, the* V wave of the jugular tracing.

Blood leaves the thorax during *the dicrotic wave,* forced by the elastic retraction of the aorta, in an amount larger than that of the blood entering the right atrium Therefore, a suction effect is created and a negative wave D_2 occurs (second diastolic wave) This coincides approximately with the wave of rapid filling of the apex cardiogram and with the 3d sound

Additional waves may occur when diastole is prolonged as the result of variations in pressure within *the thorax. They are called* D_3, D_4, etc (late diastolic waves).

RESPIRATORY VARIATIONS

Normal subjects show deeper waves during the first part of *inspiration.* However, two waves may combine in a single one. The A wave is *deep and broad,* P_2 *is smaller and of a short* duration, V_1 and V_2 tend to fuse into a single, negative, systolic wave Normal subjects present smaller waves during *expiration,* especially in the second half of the phase Wave P_1 is usually clearly defined and sharp; P_2 is tall, broad, and definitely positive, *T* is low, *S* is taller and often well defined (Fig. 4-154).

INSPIRATORY AND EXPIRATORY STANDSTILLS

The use of a crystal microphone and high-pass filter eliminates the necessity of the patient holding his breath in extreme positions and avoids individual variations and abnormal pressure conditions However, the author compared these extreme phases of apnea with the technique of normal respiration The degree of inspiration or expiration is a variable *depend-*

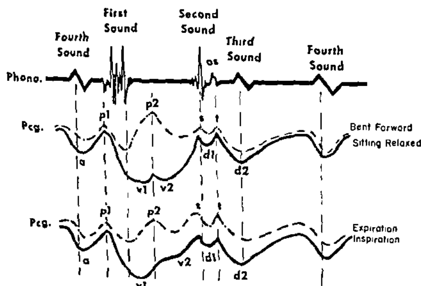


Fig. 4-154. Modifications of the pneumocardiogram (*Pcg*) caused by changes in position (*bent forward, sitting relaxed*) or respiration (*expiration, inspiration*).

ing upon the training and cooperation of the patient, and greater or lesser effect upon the waves was found. No fundamental difference in timing or polarity of the waves was found between the changes produced by normal respiratory phases and those resulting from apnea in the extreme positions.

CHANGES DUE TO POSITION

The best tracings are obtained in either *a sitting or a semirecumbent position,* with the muscles completely relaxed. Other positions, such as supine, sitting erect, sitting bent forward, or standing, may produce important changes in the internal pneumocardiogram (Fig. 4-151). Many of these changes were studied by Holzloehner, and explained as the result of an altered venous flow caused by modified tension of the venous walls.

ABNORMAL TRACINGS

Bradycardia and Tachycardia. Because of short diastole, subjects with tachycardia often show partial or total fusion of D_2 with A and small amplitude of D_1. These variations are explained by changes in diastolic venous inflow and abrupt systolic collapse of the veins. In bradycardia, the waves are typical, and additional waves may occur during diastole

Valvular Defects. In *aortic insufficiency,* the *systolic waves are very deep.* There may be only a deep V_1 or a fusion of V_1 with V_2 *The notch S is high and the notch T is even higher* This is due directly to the regurgitation of blood into the left ventricle.

In *tricuspid insufficiency,* there is *a deep negative systolic wave* (fusion of V_1 with V_2) followed by *a positive early-diastolic wave.* The succession of the negative and positive waves may cause a very impressive movement of air. This was proved by the author in 1943.

Pericarditis. In *constrictive pericarditis,* an abnormal phenomenon, consisting of *the inversion of the normal systolic waves,* has been described (Hochrein and Weiss). In the author's subjects, the waves were of normal type but smaller than in normal subjects. The difference in the findings may be explained by different criteria used in the selection of the patients.

ESOPHAGOCARDIOGRAPHY

The esophagocardiogram represents a record of cardiac motions obtained through the esophagus. One could call *esophagoatriogram* the curve recorded at the atrial level, and *esophagoventriculogram* the curve recorded at the ventricular level In addition to the movements of the heart, it is also possible to record through the esophagus the aortic pulsations (*aortoesophagogram*)

ANATOMY

During its course in the chest, the esophagus runs beside the right edge of the aortic arch, then overrides the right pulmonary hilus and the lymphatic nodules of the trachea. At 1.2 or 2 cm above the bifurcation of the trachea, it is at the midline and behind the upper part of the left atrium. Then the esophagus keeps close to the posterior part of the left atrium but deviates towards the left and crosses the descending aorta Further down and to the left, near the hiatus of the diaphragm, the esophagus leaves the inferior pole of the left atrium and crosses the posterior wall of the left ventricle. Thus, the esophagus has a close relationship with the aorta, left atrium, and left ventricle, and is separated from them only by the pericardium plus some layers of connective tissue.

HISTORY

Esophagocardiography started with the studies of Luciani (1877) who, while recording the variations of intrathoracic pressure through the esophagus, observed small waves, synchronous with the cardiac pulsations Frédéricq (1887) recorded the esophagocardiogram of dogs with a rubber balloon connected to a Marey capsule. He described a presystolic positive wave, one negative and two positive waves in systole, and a negative wave in early or middiastole. In human beings, the first esophagocardiogram was recorded by Sarolea with a similar system Further studies have been done by Minkowski, Rautenberg, and Young and Hewlett, who used the sphygmomanometer of Jaquet with an air transmission. The tracings obtained were similar to those previously described and received a similar interpretation Afterwards, esophagocardiography was used by few workers and did not become part of the usual clinical methods. Lian (1909) described a large presystolic wave and a reduction of the steepness of the curve at the middle of systole, both occurring in mitral insufficiency. Taquini (1936) published a mono-

graph devoted to the esophageal exploration of the cardiac activity, he used a capsule of Frank with air transmission He described the tracings obtained at different levels, and a wave of regurgitation in early systole as an indication of mitral insufficiency.

The new interest which cardiac surgery has brought to the diagnosis of mitral valve diseases,

modern technique.

METHODS

Generally, the cardiac movements are recorded through a rubber balloon tied to the tip of a rubber or plastic catheter (of small diameter) introduced into the esophagus. The balloon is arrested at various levels according to the chamber which one wishes to explore. at 25 to 30 cm from the dental arch, in order to obtain a tracing of the aortic arch; at 30 to 40 cm, for tracings of the left atrium, at 40 to 45 cm, for tracings of the left ventricle. If the catheter or its tip is radiopaque, it is easier to check its position by fluoroscopy. The cardiac movements determine changes in pressure in the balloon; these are transmitted through the catheter and are registered on different types of apparatus: capsule of Marey with mechanical recording; capsule of Frank with optical recording, linear microphone or electromanometer with electrical recording. Either air or water has been used as transmitting medium. The exploring balloon is kept extended either by a thin metal spiral or by means of pressure (30 to 40 mm Hg). Friese used a small electrostatic microphone placed at the tip of the catheter and lying against the esophageal wall, thus, he was able to eliminate the need for a transmitting medium The tracings have been recorded on smoked paper or photographic film, and, more recently, by means of the camera of an electrocardiograph

The test is performed with the patient in the sitting position and during a phase of expiratory apnea. Another tracing of cardiac activity should be recorded simultaneously for the timing of the waves, the best being the phonocardiogram.

ANALYSIS OF THE WAVES

The esophagocardiographic tracing is the result of the variations of intraesophageal pressure related with the movements of the cardiac chambers and large vessels close to the esophagus at a particular level. These movements are rather complex, they are in fact related to the variations of form and volume of the organs involved, because of the various phases of contraction and dilatation. The form of the wa

ex

particularly studied. The waves transmitted by the atrium to the esophagus are rather similar to those recorded in a tracing of pressure, as proved by Lasser and Loewe in animals, and by van den Heuvel-Heymans and others in clinical cases. The atrial activity causes variations in form and volume of the atrium; some of them are purely passive (filling = dilatation), while others are active (contraction). As the atrial wall is elastic, there is in the atrium (as in all elastic systems) a definite relationship between pressure and volume. During the phase of passive variation of volume, there will be a direct relationship between the esophagoatriogram (expression of these variations) and the changes of atrial volume and pressure. During the phase of active contraction, there may be either a negative wave or a positive wave caused by a modification of form of the chamber. In the latter instance, there is no relationship between the wave of the esophagogram and that of intraatrial pressure.

THE NORMAL ESOPHAGOCARDIOGRAM

The ventricular esophageal tracing is recorded at the lowest part of the thoracic esophagus, where it is in direct contact with the left ventricle The tracing shows the following waves: (1) A positive or negative wave (called AS wave by the South American authors) It appears a few hundredths of a second after the peak of the P wave of the ECG, and is due to atrial contraction. (2) A positive wave (VS wave) which begins at the peak of the R wave of the ECG, and is the expression of ventricular systole, (3) a positive diastolic wave (wave III), the peak of which coincides with the 3d sound (Fig. 4-155A).

The atrial esophageal tracing is recorded in the esophageal segment which is in contact with the left atrium It is characterized by various positive and negative waves (Fig. 4-

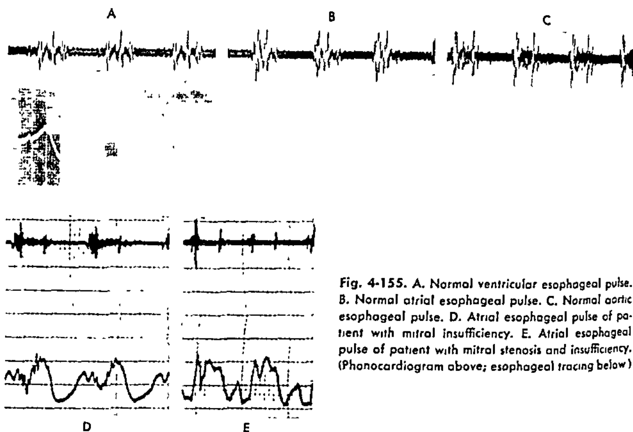


Fig. 4-155. A. Normal ventricular esophageal pulse. B. Normal atrial esophageal pulse. C. Normal aortic esophageal pulse. D. Atrial esophageal pulse of patient with mitral insufficiency. E. Atrial esophageal pulse of patient with mitral stenosis and insufficiency. (Phonocardiogram above; esophageal tracing below)

155B) The first wave is negative and occurs in presystole. It begins 0 05 sec after the P wave of the ECG and lasts for 0.13 sec It is caused by atrial contraction and is called *atrial contraction wave.* A positive wave begins 0.05 sec after the Q wave of the ECG and has a notch which coincides with the 1st heart sound This wave is related to the passive variations in the volume and shape of the left atrium during the phase of ventricular tension. In this period, there is a temporary elevation of the AV ring[2] The next wave is negative and is caused by the decreased atrial volume which occurs during the ejection period This negative wave may be divided in two by a small peak.[3] Following a small notch in coincidence with the 2d sound, there is a higher negative wave which coincides with the 3d sound and the rapid filling of the ventricle, a stage in which the left atrium is decreasing in volume.

The waves of the esophageal tracing show changes in amplitude and form according to the cardiac rate, the P-Q interval of the ECG, the position of the patient, and the phase of respiration.

The aortic tracing is recorded by placing the catheter at the level where the esophagus crosses the aortic arch. Its form is similar to that of an aortic pulse, the incisura is easily visible and coincides with the 2d sound (Fig 4-155C).

PATHOLOGICAL ATRIAL PULSATIONS

Mitral Insufficiency. In mitral insufficiency, the alterations in volume of the left atrium are accompanied by typical variations in the esophageal tracing at the atrial level. Characteristic of mitral insufficiency is the presence of a new positive systolic wave, called "insufficiency wave." This wave begins a few hundreths of a second after the 1st sound. It is often possible to observe vibrations (thrill) on the ascending branch of this wave. The wave reaches its peak in late systole or at the time of the 2d sound, then the curve drops rapidly (Fig 4-155D)

This new wave, which replaces the normal negative wave or the oblique line of atrial filling, is caused by the reflux of blood through the insufficient mitral valve during ventricular contraction. The amplitude of this wave is related to the severity of regurgitation (which

[2] This wave corresponds to the AV notch recorded by Luisada and Liu in the left atrium *Editor*

[3] For the interpretation of this, one may compare the tracing with the "internal pneumocardiogram" (Pneumocardiography, above). Both are influenced by changes of intrathoracic pressure. *Editor.*

is related on the one hand to the anatomic conditions of the valve and, on the other, to the diastolic filling of the left ventricle and the power of its contraction). It is also related to the size of the left atrium: the larger the atrium, the smaller the reflux wave

Van den Heuvel-Heymans arrived at the conclusion that the existence of mitral insufficiency can be definitely admitted or excluded *according to the form of the esophageal curve.*

Mitral Stenosis. In mitral stenosis the changes in the esophageal tracing vary according to the degree of stenosis and to the condition of the left atrium. In a first stage, when the stenosis is moderate, only an increase in the negative presystolic wave has been noticed. In these cases, the left atrium is not yet dilated and the strong atrial contraction is able to overcome the block When the obstacle is greater and the left atrial volume is increased, this wave may disappear In such cases, it should be considered that the atrial wall is always under tension. In even more severe cases, there may be a small positive wave *lasting throughout systole*

According to Friese, there is a *positive plateau*[4] *during ventricular systole, instead of* a negative wave (Fig. 4-155E).

[4] Luisada and Liu interpret this as due to moderate regurgitation in cases with severe stenosis (Chap. 12, Patterns of Pressure). *Editor.*

Blood studies

Normal Values in Blood

MARIO STEFANINI AND FRANCO GOBBI

Coagulation of the Blood

ARMAND J. QUICK

Determination of Serum Enzymes (Transaminase and Dehydrogenase)

BENJAMIN N. HORWITT

Serology and Bacteriology

JULIUS GOLDBERG AND JAMES G. SHAFFER

NORMAL VALUES IN BLOOD

Several reasons may be quoted why a chapter on the normal values in blood belongs in a book devoted to cardiology. There are obvious correlations in physiological and pathological states between blood values, circulatory, and respiratory functions Thus, diseases of the circulatory system are reflected in important blood changes, and these, in turn, may help in their recognition. In acute myocardial infarction, to cite a single example, changes in the white blood cell (WBC) count, blood sedimentation rate, and serum level of enzymes (such as glutamic oxaloacetic acid transaminase and lactic acid dehydrogenase) rank in importance with and may precede the alterations in the ECG. They are, then, of significant diagnostic and, especially, prognostic value With increasing frequency the cardiologist complements the information derived from physical and laboratory findings of his own specialties with the study of morphological, chemical, and enzymatic changes in the blood Conversely, primary hematologic disease states may affect cardiac and vascular functions Progressive failure of the myocardium reflects the histological alterations in the muscular fibers often found in *severe chronic anemias*, especially pernicious anemia, and leukemic states Finally, the increasing use by the cardiologist of anticoagulants and of drugs which may adversely affect the hematopoietic system (quinidine, etc.) makes necessary a working knowledge of the constants used to control anticoagulant therapy and to detect at an early time any possible hematologic complications of treatment.

The tabular form has been preferred to a long presentation of the subject. This not only promotes brevity, but also allows the introduction of additional data, such as statistical deviations. Without going into controversial definitions, the authors have considered "normal" the value most commonly found in a hospital population among individuals in whom the data under study were not apparently affected by disease. Data from the authors' experience have been correlated with others collected from the literature [1] Although these data

[1] (1) Albritton, "Standard Values in Blood," USAF, Wright-Patterson Base, Dayton, 1951, (2) Fulton, *A Textbook of Physiology*, Saunders, Philadelphia, 1949, (3) Rourke, "Normal Laboratory Values," *New England J. Med*, 254 29, 1956, (4) Sunderman and Boerner, *Normal Values in Clinical Medicine*, Saunders, Philadelphia, 1949, (5) Wintrobe, *Clinical Hematology*, Lea & Febiger, Philadelphia, 1956.

TABLE 4-13 PHYSICAL PROPERTIES OF BLOOD

	Average value	*Range*	*Temperature at which determination is made, °C*
Blood volume, ml/kg body wt:			
Whole blood, male	77.7	70-97	
Whole blood, female	66.1	46-85	
pH:			
Arterial blood	7.35	7.30-7.41	37
Venous blood	7.32	7.27-7.37	37
Specific gravity:			
Copper sulfate method:			
Whole blood	1.056	1.052-1.061	25
Formed elements *	1.098	1.095-1.101	25
Plasma	1.024	1.022-1.026	25
Gravimetric method:			
Formed elements *	1.099	1.094-1.107	25
Plasma	1.028	1.026-1.031	25
Viscosity (water = 1):			
Whole blood	4.7	3.9-5.3	38
Plasma	1.8		38
Serum	1.5		38
Electrophoretic mobility of red cells, cm^2/volt/sec	1.31×10^{-4}		
Electrical conductivity of serum, mhos × 10,000	113	106-120	23
Depression of the freezing point, serum, Δ - °C	0.562	0.555-0.570	
Refractive index of serum	..	1.3485-1.3505	20
Specific heat, cal			
Formed elements *	0.77		
Plasma	0.94		
Osmotic pressure of serum, mm water	330	280-480	0-37

* Primarily red cells

are those available to the authors from personal experience and careful search of the literature, omissions are possible. Values have been divided into several major categories physical properties, formed elements, and chemical constants. Because of their growing implications in medicine, enzymes and electrophoretic analyses of serum have also been introduced in this chapter. Wherever possible, statistical deviations as well as values have been indicated. Also, in many instances, values have been given separately for whole blood, plasma, or serum, and one or more of the formed elements of the blood

PHYSICAL CONSTANTS

Table 4-13 shows a variety of physical properties. While many of them are primarily of interest to the investigator, such constants as blood volume, specific gravity, viscosity, are of clinical interest. Of similar interest are the contents of Table 4-14, showing tension of gases in the arterial and venous sides of the circulation. Table 4-15 gives a summary of val-

TABLE 4-14 TENSION OF GASES IN BLOOD (in mm Hg)

	Arterial blood		*Venous blood*	
	Male	*Female*	*Male*	*Female*
Oxygen				
Total	94	94	40	41
Free	94	94	40	41
Combined	94	94	40	41
Carbon dioxide:				
Total	40	39	46	43
Free	40	39	46	43
Combined	40	39	46	43
Nitrogen	573	573	573	573

11

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Several reasons may be quoted why a chapter on the normal values in blood belongs in a book devoted to cardiology. There are obvious correlations in physiological and pathological states between blood values, circulatory, and respiratory functions. Thus, diseases of the circulatory system are reflected in important blood changes, and these, in turn, may help in their recognition. In acute myocardial infarction, to cite a single example, changes in the white blood cell (WBC) count, blood sedimentation rate, and serum level of enzymes (such as glutamic oxaloacetic acid transaminase and lactic acid dehydrogenase) rank in importance with and may precede the alterations in the ECG. They are, then, of significant diagnostic and, especially, prognostic value. With increasing frequency the cardiologist complements the information derived from physical and laboratory findings of his own specialties with the study of morphological, chemical, and enzymatic changes in the blood Conversely, primary hematologic disease states may affect cardiac and vascular functions Progressive failure of the myocardium reflects the histological alterations in the muscular fibers often found in *severe chronic anemias*, especially pernicious anemia, and leukemic states Finally, the increasing use by the cardiologist of anticoagulants and of drugs which may adversely affect the hematopoietic system (quinidine, etc.) makes necessary a working knowledge of the constants used to control anticoagulant therapy and to detect at an early time any possible hematologic complications of treatment.

The tabular form has been preferred to a long presentation of the subject. This not only promotes brevity, but also allows the introduction of additional data, such as statistical deviations. Without going into controversial definitions, the authors have considered "normal" the value most commonly found in a hospital population among individuals in whom the data under study were not apparently affected by disease. Data from the authors' experience have been correlated with others collected from the literature.[1] Although these data

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Table 4-13 Physical Properties of Blood

	Average value	*Range*	*Temperature at which determination is made, °C*
Blood volume, ml/kg body wt*			
Whole blood, male	77.7	70–97	
Whole blood, female	66.1	46–85	
pH			
Arterial blood	7.35	7.30–7.41	37
Venous blood	7.32	7.27–7.37	37
Specific gravity			
Copper sulfate method.			
Whole blood	1.056	1.052–1.061	25
Formed elements *	1.098	1.095–1.101	25
Plasma	1.024	1.022–1.026	25
Gravimetric method			
Formed elements *	1.099	1.094–1.107	25
Plasma	1.028	1.026–1.031	25
Viscosity (water = 1)*			
Whole blood	4.7	3.9–5.3	38
Plasma.	1.8		38
Serum	1.5		38
Electrophoretic mobility of red cells, cm²/volt/sec	1.31×10^{-4}		
Electrical conductivity of serum, mhos $\times$ 10,000	113	106–120	23
Depression of the freezing point, serum, Δ – °C	0.562	0.555–0.570	
Refractive index of serum		1.3485–1.3505	20
Specific heat, cal.			
Formed elements *	0.77		
Plasma	0.94		
Osmotic pressure of serum, mm water	330	280–480	0–37

* Primarily red cells

are those available to the authors from personal experience and careful search of the literature, omissions are possible Values have been divided into several major categories physical properties, formed elements, and chemical constants Because of their growing implications in medicine, enzymes and electrophoretic analyses of serum have also been introduced in this chapter. Wherever possible, statistical deviations as well as values have been indicated Also, in many instances, values have been given separately for whole blood, plasma, or serum, and one or more of the formed elements of the blood

PHYSICAL CONSTANTS

Table 4-13 shows a variety of physical properties While many of them are primarily of interest to the investigator, such constants as blood volume, specific gravity, viscosity, are of clinical interest Of similar interest are the contents of Table 4-14, showing *tension of* gases in the arterial and venous sides of the circulation Table 4-15 gives a summary of val-

Table 4-14 Tension of Gases in Blood (in mm Hg)

	Arterial blood		*Venous blood*	
	Male	*Female*	*Male*	*Female*
Oxygen				
Total	94	94	40	41
Free	94	94	40	41
Combined	94	94	40	41
Carbon dioxide				
Total	40	39	46	43
Free	40	39	46	43
Combined	40	39	46	43
Nitrogen	573	573	573	573

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Blood studies

Normal Values in Blood
MARIO STEFANINI AND FRANCO GOBBI

Coagulation of the Blood
ARMAND J. QUICK

Determination of Serum Enzymes (Transaminase and Dehydrogenase)
BENJAMIN N. HORWITT

Serology and Bacteriology
JULIUS GOLDBERG AND JAMES G. SHAFFER

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TABLE 4-13. PHYSICAL PROPERTIES OF BLOOD

	Average value	Range	*Temperature at which determination is made, °C*
Blood volume, ml/kg body wt:			
Whole blood, male	77 7	70–97	
Whole blood, female	66 1	46–85	
pH			
Arterial blood	7 35	7.30–7 41	37
Venous blood	7.32	7.27–7.37	37
Specific gravity			
Copper sulfate method.			
Whole blood	1 056	1 052–1 161	25
Formed elements *	1 098	1 095–1 101	25
Plasma	1 024	1 022–1 026	25
Gravimetric method:			
Formed elements *	1 099	1 094–1 107	25
Plasma	1 028	1.026–1 031	25
Viscosity (water = 1)			
Whole blood	4 7	3 9–5 3	38
Plasma	1 8		38
Serum	1 5		38
[illegible]	1 31 × 10^{-4}		
[illegible]	113	106–120	23
[illegible]	0 562	0 555–0 570	
Refractive index of serum		1 3485–1.3505	20
Specific heat, cal			
Formed elements *	0 77		
Plasma	0 94		
Osmotic pressure of serum, mm water	330	280–480	0–37

* Primarily red cells

are those available to the authors from personal experience and careful search of the literature, omissions are possible Values have been divided into several major categories physical properties, formed elements, and chemical constants Because of their growing implications in medicine, enzymes and electrophoretic analyses of serum have also been introduced in this chapter Wherever possible, statistical deviations as well as values have been indicated Also, in many instances, values have been given separately for whole blood, plasma, or serum, and one or more of the formed elements of the blood

PHYSICAL CONSTANTS

Table 4-13 shows a variety of physical properties. While many of them are primarily of interest to the investigator, such constants as blood volume, specific gravity, viscosity, are of clinical interest. Of similar interest are the contents of Table 4-14, showing tension of gases in the arterial and venous sides of the circulation. Table 4-15 gives a summary of val-

TABLE 4-14 TENSION OF GASES IN BLOOD
(in mm Hg)

	Arterial blood		*Venous blood*	
	Male	*Female*	*Male*	*Female*
Oxygen				
Total	94	94	40	41
Free	94	94	40	41
Combined	94	94	40	41
Carbon dioxide:				
Total	40	39	46	43
Free	40	39	46	43
Combined	40	39	46	43
Nitrogen	573	573	573	573

TABLE 4-15. ERYTHROCYTE SEDIMENTATION RATES *

(as determined by various methods)

Method	Range, mm/hr		
	Adult		Child
	Male	Female	
Cutler	0-8	0-10	4-13
Landau	0-6	0-9	
Smith	0-10	0-10	3-13
Walton	0-8	0-8	
Westergren	0-15	0-20	
Wintrobe and Landsberg	0-9	0-15	

* Measured at the end of one hour. Rates decrease asymptotically in succeeding hours

ues for blood sedimentation rate with various procedures.

FORMED ELEMENTS

A description of each formed element of the blood appears unnecessary. Figure 4-156 shows, for quick reference, a composite slide including all elements which may be found in the circulating blood under normal conditions. Table 4-16 shows a multiplicity of values for the *red blood cells* (chemical constituents are not included, but appear in other tables). Figure 4-157A shows graphically the osmotic fragility of erythrocytes, including values for adults and infants. Figure 4-157B shows the influence of altitude on number of red blood cells (RBC) and concentration of hemoglobin. Figure 4-158A indicates variation in RBC count, hematocrit, and hemoglobin during pregnancy and the postpartum period

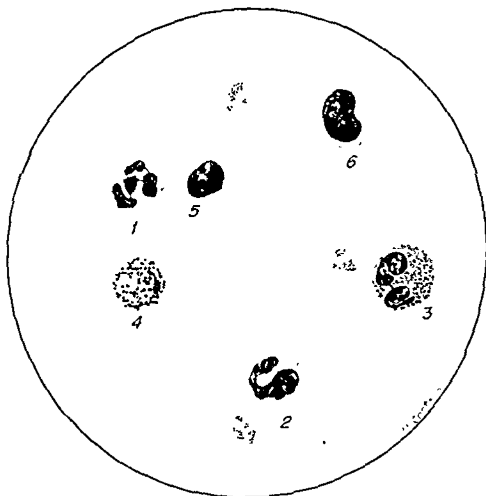


Fig. 4-156. Formed elements in normal human peripheral blood (schematic). 1, *Mature neutrophil*; 2, *metamyelocyte*; 3, *eosinophil*; 4, *basophil*, 5, *lymphocyte*; 6, *monocyte*. Clumps of platelets are also present.

Table 4-17 includes numerical values for *leucocytes*. Physical properties and chemical constituents are not included since they are of little practical diagnostic value at the present time. Figure 4-158B shows the influence of age on the absolute and differential leucocyte count. No special effort has been made to present numerical values for *platelets*. There is a growing feeling that most methods of counting the latter are grossly inadequate and certainly

TABLE 4-16. CHEMICAL AND PHYSICAL PROPERTIES OF ERYTHROCYTES AND HEMOGLOBIN

	Adult male		*Adult female*		*Child*		*Symbol*
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*	
Count, millions/mm³ blood	5.4	4.6-6.2	4.8	4.2-5.4	4.8	3.8-6.0	
Mean diameter,[a] microns							*MCD*
Fixed	7.5	7.2-7.8	7.5	7.2-7.8			
Wet	8.4	7.4-9.4	8.4	7.4-9.4			
Mean corpuscular thickness,[b] microns							MCT
Fixed	2.0	1.7-2.2	2.0	1.7-2.2			
Wet	2.4		2.4				
Surface area, μ^2							
Fixed	135	129-146	135	129-146			
Wet	163		163				
Mean mass,[c] $\mu\mu g$	96	77-103					
Specific gravity	1.0983	1.095-1.101	1.0983	1.095-1.101			
Iron content, $\mu\mu g$/cell	0.10	0.08-0.12	0.10	0.08-0.12			
Electrical charge, mv	16.8		16.8				
Electrophoretic mobility cm²/volt/sec	1.31×10^{-4}		1.31×10^{-4}				
pH	7.24	7.21-7.26	7.24	7.21-7.26			
Life span, days	120		109				
Oxygen consumption, $\mu l\ O_2$/mg dry wt/hr							
In serum	−0.018		−0.018				
In Ringer's solution	−0.017		−0.017				
Hemoglobin concentration, Gm/100 ml blood	15.8	14-18	13.9	11.5-16	18	13-22	Hb or *Hgb*
Hematocrit reading, red-cell packed volume, per cent	47	40-54	42	37-47	51	41-61	Ht
Mean corpuscular hemoglobin,[d] $\mu\mu g$	29	25-34	28	24-33			*MCH*
Mean corpuscular volume,[e] μ^3	87	70-94	87	74-98	113	90-124	MCV
Mean corpuscular hemoglobin concentration,[f] Gm/100 ml packed erythrocytes	33.5		33.5		37	32-43	MCHC
Color index[g]	1.00	0.85-1.15	1.00	0.85-1.15			CI
Daily erythrocyte production							
RBC/mm³	45,000		40,000				
RBC/kg body wt	$3,500 \times 10^6$		$2,630 \times 10^6$				
Daily RBC replacement, per cent	0.83		0.83				
Daily hemoglobin production, Gm/100 ml blood	0.13		0.11				
Daily hemoglobin replacement per cent	0.83		0.83				

[a] Mean red cell diameter is obtained by microscopic observation of at least 1,000 red cells with micrometric ocular.

[b] $\text{Mean corpuscular thickness} = \dfrac{\text{mean corpuscular volume}}{\pi\,(\text{mean diameter}/2)^2}$

[c] Mean erythrocyte mass = mean corpuscular volume × erythrocyte specific gravity

[d] $\text{Mean corpuscular hemoglobin} = \dfrac{\text{hemoglobin (Gm/100 ml blood)} \times 10}{\text{erythrocyte count (millions/mm}^3)}$

[e] $\text{Mean corpuscular volume} = \dfrac{\text{hematocrit reading} \times 10}{\text{erythrocyte count (millions/mm}^3)}$

[f] $\text{Mean corpuscular hemoglobin concentration} = \dfrac{\text{hemoglobin (Gm/100 ml blood)}}{\text{hematocrit reading}}$

[g] $\text{Color index} = \dfrac{\text{hemoglobin per cent (Gm/100 ml blood} \times 6.9)}{20 \times \text{red cell count (millions/mm}^3)}$

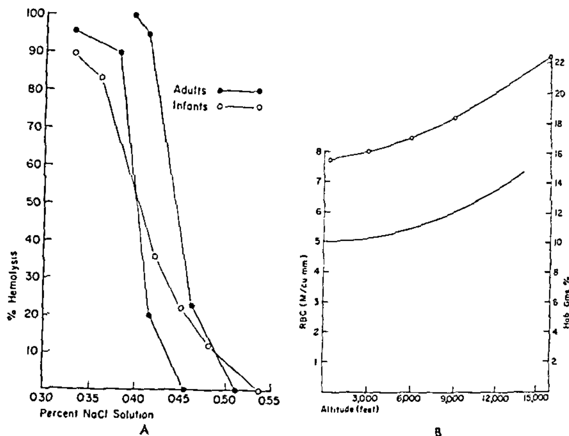


Fig. 4-157. A. Osmotic fragility of human erythrocytes as determined by a quantitative method (*From Whitby and Hynes, 1935*) B. The influence of altitude on the number of circulating erythrocytes and on the concentration of hemoglobin. Values are given for adults (ranges) and infants (average).

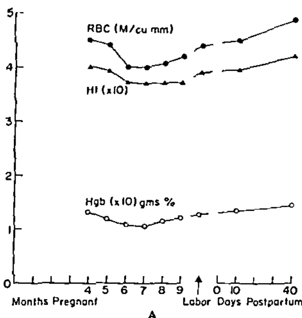


Fig. 4-158. A Erythrocytes, hematocrit, and hemoglobin values during pregnancy and the postpartum period. B. Average total and differential leukocyte count from birth to adult life. C. Ionic balance and buffer base in arterial blood, cells, and plasma. Values shown in these diagrams are for adult males. X^-, undetermined anion residue; HbO_2^- includes other cell buffer ions, such as organic phosphate; *pH* of whole blood, plasma pH; pCO_2, CO_2 *tension; B*, mEq total base (Na^+, K^+, etc.) in 1 liter blood on basis of hematocrit value of 45 per cent

WBC (x 1000)

23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0

WBC

N

L

M

8 12 24 Hours

1 2 4 Weeks

2 4 6 8 10 12 Months

2 4 6 8 10 12 14 16 18 20 22 Years

B

	PLASMA		RED CELLS		BLOOD	
	Cation	Anion	Cation	Anion	Cation	Anion
Total	150		119		136	
Buffer Base	42		57		49	
	Na^+ 139	Protein$^-$ 16	K^+ 95	"HbO_2^-" 42	B^+ 136	Protein$^-$ 28
	K^+ 4.2	HCO_3^- 26	Na^+ 18.6	HCO_3^- 15		HCO_3^- 21
	Ca^{++} 5.2	Cl^- 103	Mg^{++} 5.1	Cl^- 52		Cl^- 80
	Mg^{++} 1.7	X^- 5		X^- 10		X^- 7
	Vol. 55%		Vol 45%		Vol. 100%	
	pH 7.39		pH 7.19		pH 7.39	
	pCO_2 41mm		pCO_2 41mm		pCO_2 41mm	

mEq/liter 0 50 100 150

C

cells; buffer base is that quantity of total base equivalent in amount (in terms of mEq) to the labile portion of the total anions, i.e., proteinate, bicarbonate, oxyhemoglobinate, organic phosphate, and other red cell buffer ions (*From Standard Values in Blood* Albritton, ed)

TABLE 4-17. NORMAL DIFFERENTIAL LEUCOCYTE COUNT

Type of leucocyte	*Average count, absolute number/mm³*	*Range*	
		Absolute number/mm³	*Per cent*
Neutrophil			
Non-segmented	200	50–400	3–5
Segmented	4,200	3,000–6,000	51–62
Total	4,400	3,000–6,500	57–67
Eosinophil	200	50–350	1–3
Basophil	40	15–100	0–0 75
Lymphocyte	2 100	1 500–3,000	25–33
Monocyte	300	200–500	3–7
Leucocytes, total count/mm³	7,100	5,000–10,000	100

no better than the direct observation of a well-spread, well-stained smear The following figures summarize ranges for platelet counts·

Direct methods: 200,000 to 300,000 platelets/mm

Indirect methods: 400,000 to 800,000 platelets/mm

The statement that the platelet count is approximately 12 per cent higher in venous than in capillary blood has not been substantiated and the difference is well within the experimental error of the methods used.

CHEMICAL CONSTANTS

Table 4-18 gives data on the proportion of *water and solids in blood, plasma, serum, and* erythrocytes. Data regarding the status of gases in whole blood, arterial and venous, are summarized in Table 4-19. Electrolytes of clinical importance are presented in Table 4-20. The same table also shows values for the other blood minerals, most of which are trace elements. Because of the complexity of their status in blood, phosphorus and sulfur are discussed in Tables 4-21 to 4-23. Values for nonprotein nitrogen compounds and for amino acids are shown in Tables 4-24 and 4-25, respectively. Quantitative values for total proteins and their fractions are given in Table 4-26. Both salting-out and electrophoretic procedures have been considered. Some of the important physical properties of plasma proteins are shown in Table 4-27. Because of the recent emphasis on lipid metabolism and its relationship to development of lesions of the vascular intima, blood lipid partition is given in detail in Table 4-28. Values for most blood carbohydrates are included in Table 4-29.

VARIOUS CONSTITUENTS WITH BIOLOGICAL ACTIVITY

Blood content of various vitamins is shown in Table 4-30. Blood hormone values are shown in Table 4-31, although the available information is extremely limited. Enzymes found in whole blood, plasma, or erythrocytes are shown in Table 4-32. The verbosity of the table is justified by the extreme diversity in unitage.

COMPREHENSIVE TABLES

Table 4-33 includes acid-base values *in ar*terial, capillary, and venous blood of various age groups. Although the table is repetitive of values previously presented, it is of use for

TABLE 4-18 WATER AND TOTAL SOLIDS CONTENT OF ADULT BLOOD

(in Gm per 100 ml)

	Water		*Solids*	
	Average value	*Range*	*Average value*	*Range*
Whole blood	83	81–86	23	20–25
Plasma .	94	93–95	8 60	7 90–9 10
Serum	93	93–94	8.30	7 55–9 45
Erythrocytes .	73	70–75	37	34–39

TABLE 4-19 GAS CONTENT OF WHOLE BLOOD

(in ml per 100 ml)

Gas	*Arterial blood*		*Venous blood*	
	Male	*Female*	*Male*	*Female*
Oxygen				
Total	20 3	17 9	15.3	13 7
Free	0 285	0 282	0 122	0 124
Combined	20	17 6	15 2	13 6
Oxygen capacity			20 4	18 0
Carbon dioxide				
Total	49 0	48 0	53 1	51 4
Free	3 384	2 532	2 997	2 785
Combined				
Total	45 6	45 5	50 1	48 7
Carbamino	2 2	1 9	3 1	2 7
Bicarbonate	43 4	43 5	47.0	46 0
Nitrogen .	0 979	0 970	0.979	0 970

quick working reference. Figure 4-158C is a summary of the ionic balance and buffer base in plasma, erythrocytes, and blood, again for quick reference.

HEMOSTATIC AGENTS

The platelet count has already been discussed Values for whole blood clotting time, bleeding time, and concentration of prothrombin, and their variations in normal subjects are shown in Fig 4-159 Values for fibrinogen are given in Table 4-27. The absolute concentration of prothrombin is given in Table 4-27. Values for other factors of the clotting mechanism are usually expressed as per cent activity, 100 per cent being the theoretical normal value. It is well known, however, that considerable variations (up to 60 per cent or more) may be found in otherwise normal individuals, without evidence of bleeding tendency or of hypercoagulability. Another system of expressing values for clotting factors is by means of units Normal units for some of these agents are indicated in Table 4-27 (footnote).

TABLE 4-20A INORGANIC ION CONTENT OF BLOOD
(in mEq per L *)

Ion	*Whole blood*		*Serum*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Sodium (Na^+)	85 4	79 3-91	137	134-141	21 2	15.7-25 3
Potassium (K^+)	45	40-48	4 4	3.1-5 3	95	90-100
Calcium (Ca^{++})			5	4 5-5 3		
Magnesium (Mg^{++})			1 7	1 4-2 4	5	
Chlorides (Cl^-)	80	73-87	101	97-105	52	
Bicarbonate (HCO_3^-)			27	24-31		
Phosphate (PO_4^{-3})			2 4	1 9-3 8		
Sulfate ($SO_4^=$)			0 7	0 4-1 0		

TABLE 4-20B INORGANIC ELEMENTS IN BLOOD
(in µg per 100 ml)

Elements	*Whole blood*		*Serum*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Aluminum	15		46		7	
Bromine				0 7-1 0		
Copper	94	73-115	110	78-143	75	49-101
Fluorine			28	10-45	28	10-45
Iodine	7 7	3-13	7 1	4 8-8 6		
Iron	48	43-52	105	32-177		
Lead	29	18-49	2 9			
Manganese	15	0-25	8		57	29-86
Tin	20		4		19	
Zinc	880	490-1270	300		26	
					1,440	910-1970

* To convert mEq/L to mg/100 ml, multiply mEq/L values by the following constants sodium, 2.3, potassium, 3 9; calcium, 2 0, magnesium, 1 2; chlorides, 3 5, bicarbonate, 2 3, phosphate, 1 8; sulfate, 1 6

TABLE 4-21. BLOOD PHOSPHORUS, INORGANIC AND ORGANIC
(in mg per 100 ml)

Substance	*Whole blood*		*Plasma*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Phosphorus:						
Inorganic	2.9	2 1-3.8	4.2	2-5	2.4	0 90-3.3
Organic, acid-soluble	23.0	18-29	4.0	2.5-5 5	50.0	30-59
Total				8-18	. .	47-114
Phosphorus content of:						
Adenosine triphosphate	8.1	5.0-10.4			18.2	14-24
Diphosphoglycerate	12 4	8-16 5			29 0	19-40
Nucleotide	2.8	2 2-3.4			6.2	5-7
Lipid	11 0		8.00	5-13	15.0	11-27
Hexose phosphate	3.0	1 5-5.0	0.05	0.0-0 2	7 5	3 5-10 5

TABLE 4-22 SULFUR CONTENT OF BLOOD PLASMA
(in mg per 100 ml)

Source of sulfur	*Average value*	*Range*
In total sulfate	1 1	0 9-1 3
Inorganic sulfur	0 9	0 8-1 1
Nonprotein sulfur	2 8	2 4-3 6
Ethereal (conjugated) sulfur *	0 1	0-0 2
Organic sulfur	1 7	1 4-2.6

* Average value in erythrocytes: 0 015 mg/100 ml

TABLE 4-23 OTHER SULFUR-CONTAINING SUBSTANCES IN BLOOD
(in mg per 100 ml)

Substance	*Whole blood*		*Plasma*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Sulfate:						
Inorganic			1 1	0 8-3 3		
Conjugated			0 3	0-0.6		
Total			3 3	2 7-3 9		
Ergothioneine		1 9-5 5	0		9.6	3 9-17 7
Indican			0	0-0 6		
Thiocyanate	0 77	0 5-1 4				
Glutathione:						
Oxidized	4.0		0		8 5	
Reduced	35 0	25-41	0		79 0	
Total	39.0		0		87 5	

TABLE 4-24. NONPROTEIN NITROGEN COMPOUNDS PRESENT IN NORMAL BLOOD
(in mg per 100 ml)

Compound	*Whole blood*		*Plasma*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Adenosine triphosphate	44	31-57	.	. . . .	72	
Amino acids	50	38-53				
Ammonia	0 18	0 12-0 24				
Bilirubin			0 35	0.20-1 0		
Creatine	3 9	2 9-4 9	0 23	0-0.8	8 1	6-10.2
Creatinine	1 5	1-2	0 91	0 87-0 95	1.8	1.7-1.9
Desoxyribonucleic acid			0 8	0-1.6	Traces	
Flavoadenine dinucleotide			0.012		0 075	0.060-0.08
Glucosamine			67	61-78		
Glutamine			7	5-12		
Methylguanidine	0 25	0 2-0 3				
Nucleotides	40	30-50				
Pyridine nucleotides	3.6	2 6-4 6	.	.	7 7	6-9.3
Ribonucleic acid	64	48-79	4 9	3 9-5 9	136	100-170
Urea:						
In males	33	26-46	34	28-40	30	25-38
In females	24	11-29				
Uric acid	3 2	2 2-4 2	3.8	2-5 6	1 9	0 8-3.0

TABLE 4-25 FREE AMINO ACIDS PRESENT IN NORMAL BLOOD
(in mg per 100 ml)

Amino acid	*Whole blood*		*Plasma*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Alanine	4 0	2 8-5 2	4 0	2 6-5 3	4 0	2 5-5 6
Arginine	1 0	0 6-1 7	2 3	1 1-3 5	0 3	0 1-0 6
Aspartic acid				0 9-1 2		
Cysteine	0 3		0 2		0 5	
Cystine	0.9	0 6-1 2	1 4	0 8-2 0	0 4	0.3-0.5
Glutamic acid			0 8	0 6-1 7		
Glycine		1 8-2 5	1 8	1 3-2 3	2 4	1.6-3.1
Histidine	1 3	0 9-1 7	1 4	1.1-1 8	1.1	0 8-1.6
Isoleucine	1 3	0 9-1 5	1.6	1 0-2 2	0 9	0 5-1 4
Leucine	1.7	1 4-2.0	1 9	1 3-2 5	1 5	1 0-1.8
Lysine	2 2	1 3-3 0	3 0	2 1-3 8	1 4	0 9-1 8
Methionine	0 5	0 4-0 6	0 5	0.3-0 6	0 5	0 3-0 8
Phenylalanine	1 0	0 8-1 2	1 4	0.5-2.2	1 0	0.7-1 3
Proline				2 4-2 7		
Threonine	1 6	1 3-2 0	2 0	1 1-2 0	1 6	1 3-2 1
Tryptophan	0 7	0 5-1 0	1 1	0 7-1 5	0 24	0 2-0 4
Tyrosine	1 1	0 8-1 4	1 5	0 8-2 2	1 1	0 7-1 5
Valine	2 4	2 0-2 0	2 8	2 2-3 5	2 0	1 6-2 5

Table 4-26 Protein Content of Normal Plasma

(values obtained by different fractionation methods)

Protein	Salt * fractionation method			Electrophoretic method			Method of Winzler et al	
	Content, per cent	Content, Gm/100 ml		Content, per cent	Content, Gm/100 ml		Content, mg/100 ml	
		Average value	Range		Average value	Range	Average value	Range
Fibrinogen	3.8	0.28	0.23–0.36	4.0	0.29	0.24–0.35		
Albumins . ..	61.8	4.58	4.1–5.1	60.5	4.42	4.0–4.8		
Globulins								
α_1-Globulins				4.0	0.29	0.2–0.4		
α_2-Globulins				7.7	0.56	0.4–0.7		
β-Globulins				11.5	0.84	0.6–1.1		
γ-Globulins				12.3	0.90	0.6–1.2		
Total globulins †	34.4	2.55	1.8–3.3	35.5	2.59	1.9–3.5		
Euglobulins	21.4	1.59	0.9–2.2					
Total pseudoglobulins	13.0	0.96	0.6–1.35					
Muco protein (seromucoid)								
Hexoses . .		.			. .		6.2	
Hexosamines .					. .		11.6	
Total mucoprotein							100.0	65–165
Total plasma proteins	100	7.41	6.2–8.6	100	7.30	6.0–8.7		

* $(NH_4)_2SO_4$

† Albumin/globulin ratio with salt fractionation method, 1:8, with electrophoretic method, 1:10.

Table 4-27 Some Physical Properties of Plasma Proteins

Protein	Cohn's fraction	Proportion of plasma proteins, per cent	Isoelectric point, pH	Molecular weight	Sedimentation constant, $S_{20}W$	Length of molecule, A
Albumin	V	52	4.9	69,000	4.6	150
α_1-Bilirubin globulin	V-1	0.05	4.7			
α_1-Glycoproteins	VI-2	0.5	3.0		3.5	
α_1-Lipoproteins	IV-1	3	5.2	200,000	5	300
α_2-Globulins	VI-1	0.1			2.9	
α_2-Glycoproteins	IV-6	1.2	4.9		9	
α_2-Mucoproteins	IV-6	0.5	4.9		9	
β_1-Metal-combining proteins	IV-7	3	5.8	90,000	5	190
β_1-Globulins	VI-1	0.05			5	
β_1-Lipoproteins	III-0	5	5.4	1,300,000	7	185
β_1-Lipid-poor euglobulins	III-0	3	5.5			
β_2 Globulins	III	3	6.3		7	
γ-Globulins	II	11	6.3–7.3	150,000–300,000	7–10	235
Cold-insoluble globulin	I-1	0.15	<5.3			
Fibrinogen	I-2	4	<5.3	400,000	9	700
Antihemophilic globulin	I					
Prothrombin †	III-2	0.1				
Plasminogen	III-3					
Isoagglutinin and antibody euglobulins .	III-1	0.03	6.3			
Plasmin ‡ .	III-3					
Complement components, $C_1'C_2'$.	III-2 IV	0.4	5.2–5.4		6.4	
Mercaptalbumin	V	34				

† 330 units/ml of plasma (Ware and Seegers)

‡ Units/ml of plasma (activated) [Loomis] value uncertain

SOURCE Modified from Albritton, Standard Values in Blood

TABLE 4-28. BLOOD LIPIDS

(in mg per 100 ml)

Lipid	Whole blood		Plasma		Erythrocytes	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Total fatty acids				. . . .	316	149–483
Neutral fat	134	85–237	140	24–260	93	11–148
Phospholipids	247	186–309	165	110–220	350	280–420
Lecithin	115	.	117		70	
Cephalin	65	31–118	7		210	
Sphingomyelin	186		41	.	70	
Cholesterol.						
Free	97	82–113	46	30–62	140	119–161
Esterified	81	47–115	106	75–137	0	
Total	178	129–228	152	105–199	173	118–228
Cholesteryl esters	140	79–194 *	179 *	127–232 *	0	
Total lipids	559	397–722	530	385–675	596	411–781

* Cholesterol esters × 1 69

TABLE 4-29 BLOOD CONTENT OF CARBOHYDRATES AND RELATED COMPOUNDS

(in mg per 100 ml)

Substance	*Whole blood*		*Serum*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Glycogen *	5.5	1 2–16.2	0		0	
Polysaccharides, free			102	73–131		
Glucose	86	76–96	97	61–130	74	46–102
Fructose			7 5			
Lactose	0 to traces					
Hexuronate	6 7	4 1–9 3	0 8		0.6	
Pentose						
Total			3 7	2 6–4 8		
Phosphorylated			2 1			
Diphosphoglyceric acid					120	
Lactic acid	24		36		12	
Pyruvic acid	0 3		1 2			
α-Ketonic acid	1 3	0 0–3 1				
α-Ketoglutaric acid	0 2		0 9			
Citric acid	1 9	1 3–2 5	2 4	1 6–3 2		
Malic acid			0 5	0 1–0 9		
Succinic acid			0 5			

* White blood cells, 2.5 mg/100 ml (1 0–3.8).

Table 4-26. Protein Content of Normal Plasma

(values obtained by different fractionation methods)

Protein	Salt * fractionation method			Electrophoretic method			Method of Winzler et al	
	Content, per cent	Content, Gm/100 ml		Content, per cent	Content, Gm/100 ml		Content, mg/100 ml	
		Average value	Range		Average value	Range	Average value	Range
Fibrinogen	3.8	0.28	0.23–0.30	4.0	0.29	0.24–0.38		
Albumins	61.8	4.58	4.1–5.1	60.5	4.42	4.0–4.8		
Globulins								
α_1-Globulins				4.0	0.29	0.2–0.4		
α_2-Globulins				7.7	0.56	0.4–0.7		
β-Globulins				11.5	0.84	0.6–1.1		
γ-Globulins				12.3	0.90	0.6–1.2		
Total globulins †	34.4	2.55	1.8–3.3	35.5	2.59	1.9–3.5		
Euglobulins	21.4	1.59	0.9–2.2					
Total pseudoglobulins	13.0	0.96	0.6–1.35					
Muco protein (seromucoid)								
Hexoses							6.2	
Hexosamines							11.6	
Total mucoprotein							100.0	65–165
Total plasma proteins	100	7.41	6.2–8.6	100	7.30	6.0–8.7		

* $(NH_4)_2SO_4$

† Albumin/globulin ratio with salt fractionation method, 1.8, with electrophoretic method, 1:10.

Table 4-27. Some Physical Properties of Plasma Proteins

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α_1-Glycoproteins	VI-2	0.5	3.0		3.5	
α_1-Lipoproteins	IV-1	3	5.2	200,000	5	300
α_2-Globulins	VI-1	0.1			2.9	
α_2-Glycoproteins	IV 6	1.2	4.9		9	
α_2-Mucoproteins	IV 6	0.5	4.9		9	
β_1-Metal-combining proteins	IV-7	3	5.8	90,000	5	190
β_1-Globulins	VI-1	0.05			5	
β_1-Lipoproteins	III-0	5	5.4	1,300,000	7	185
β_1-Lipid-poor euglobulins	III-0	3	5.5			
β_2 Globulins	III	3	6.3		7	
γ-Globulins	II	11	6.3–7.3	150,000–300,000	7–10	235
Cold-insoluble globulin	I-1	0.15	<5.3			
Fibrinogen	I-2	4	<5.3	400,000	9	700
Antihemophilic globulin	I					
Prothrombin †	III-2	0.1				
Plasminogen	III-3					
Isoagglutinin and antibody euglobulins	III-1	0.03	6.3			
Plasmin ‡	III-3					
Complement components $C_1'C_2'$	III-2 IV	0.4	5.2–5.4		6.4	
Mercaptalbumin	V	34				

† 330 units/ml of plasma (Ware and Seegers)

‡ Units/ml of plasma (activated) [Loomis], value uncertain

SOURCE Modified from Albritton, Standard Values in Blood

TABLE 4-32 ENZYMES PRESENT IN BLOOD

Enzyme	Blood component	Expressed as	Average value	Range
Adenosine polyphosphatase	Serum	[illegible]	10	20–60
Acid	Serum			10–50
Alkaline	Serum			350–800
Aldolase	Serum			80–150
Amylase	RBC			2,500–7,500
Arginase	RBC			
Carbonic anhydrase		catalyzed [illegible]	—	420–950
Catalase	Serum	Dille units	547	437–660
Cholinesterase	RBC	μM/min, acetylcholine hydrolyzed	176	139–219
	Plasma		261	
	RBC	μM/min, acetylmethylcholine hydrolyzed	5 8	
	Plasma		Traces	
	RBC	μM/min, benzoylcholine hydrolyzed	110	
	Plasma			
Cocarboxylase Male	RBC	μg/100 ml (microbiological determination)	10	7–14
Female			6 5	5–8
Dehydropeptidase	Serum		359	190–520
Glyoxalase	RBC	[illegible]	1,390,000	1,320,000–1,500,000
Glutamic-oxaloacetic acid transaminase	Serum	Karmen units	19	10–32
Glutamic-pyruvic acid transaminase	Serum	Karmen units	36	5–30
				30–40
Histaminase	WBC	μg of histamine destroyed in 90 min at 37°C	18	0–36
	Serum		60	40–80
Lactic dehydrogenase	Serum	Wacker units/min		0–150
Lipase	Serum	ml N/20 NaOH needed to neutralize fatty acids freed from standard olive-oil emulsion in 24 hr		1–4
Phosphatase Acid	Serum			0–0 5
Prostatic (acid)	Serum			10–13
Alkaline	Serum	mg/hr phenol [illegible] at 37°C at pH 9		50–125
Profibrinolysin	Plasma	Units (One unit will lyse a 0 1 per cent fibrin clot in 2 hr at 28°C at pH 7 2)		

Enzyme inhibitors antistreptolysin (normal range 0 to 100 units) antifibrinolysin (normal range 140 to 165 units)

COAGULATION OF THE BLOOD

Blood has incorporated within it a finely adjustable mechanism for sealing a break or leak in the vascular system and thus preventing undue hemorrhage after injury. This hemostatic process is complex and is still poorly understood It is well recognized, however, that the coagulation of blood constitutes an important part of this mechanism, and that, when it is defective, a bleeding tendency becomes manifest Attempts to develop a simple test to detect or measure faulty coagulation have been unsuccessful The clotting time which, until recently, was the only test available to measure coagulation has serious limitations The clotting of blood in a test tube is grossly unphysiological and cannot be considered comparable to the process which occurs in the body as a response to injury Often the erroneous assumption is made that the clotting time is an overall estimate of the efficacy of the hemostatic mechanism and that the control of bleeding depends on a mechanical fibrin plug. As evidence against such assumptions, one need merely mention that hemostasis is only mildly impaired in congenital afibrinogenemia, even though no clot can form, and is seriously defective in acute thrombocytopenic purpura despite the normal concentration of fibrinogen and the normal clotting time.

THE CLASSICAL THEORY

The problem of *hemostasis* is twofold first, it demands an understanding of the chemistry of the coagulation of blood and, second, it requires a correlation of the data on clotting in a test tube with the physiological process of

Table 4-30. Vitamin Content of Normal Blood
(in units of weight per 100 ml)

Vitamin, unit of wt	*Whole blood*		*Plasma*		*Erythrocytes*	
	Average value	*Range*	*Average value*	*Range*	*Average value*	*Range*
Vitamin A, μg:						
As carotenol	13	9–17	24	10–60		
As carotene	120	20–300	220	40–540		
Thiamine (B_1), μg	8	4–11	7	1–9	8	7–10
Riboflavin (B_2), μg	27	13–85	3 2	2.6–3.7	22 4	18–26
Niacin, mg	0 65	0 5–0 8	0 07	0.025–0 15	1.3	1.2–1.5
Biotin, μg	1.2	0 8–1.7	1 3	1–1 7		
Pantothenic acid, μg *	30	15–45	15	6–35	25	15–30
p-Aminobenzoic acid, μg	3.4					
Pteroylglutamic acid, μg:						
Total	3 5	2.3–5.3	1.7	1.5–5.0		
Free	0 085	0.05–0 13	0.05			
Inositol, mg			0 5	0.35–0.75		
Vitamin B_{12}, μg	0 08	0 06–0 11				
Ascorbic acid, mg †	0 62	0 2–0 7	0 7	0 1–2 5	1.0	0.5–2 8
α-Tocopherol, mg			1 1	0.6–1 6		

* Bound pantothenic acid (coenzyme A) found only in formed elements at a concentration of 210–280 μg/100 ml

† "Buffy coat": average value, 18 5; range, 14.3-27.2 mg 100/ml

Table 4-31 Hormones * Present in Normal Blood

Hormone	*Concentration*		
	μg/100 ml	*mg/100 ml*	*Units/100 ml*
Acetylcholine, plasma	7 2 (0 6–8.2)		
Adrenocorticotropic hormone (ACTH), blood	<15		
Androgens (as testosterone)			
Male plasma		2 8 (2 1–3 4)	
Female plasma		2 7 (2 1–3 2)	
Chorionic gonadotropin, pregnant female plasma			14,000 (7 000–60,000) (international)
Corticosteroids, total			
Male plasma		0 23 (0 11–0 42)	
Female plasma		0 28 (0 13–0 42)	
Estrogens (as estradiol)			
Pregnant female blood	0 30 (0 22–0 55)		
Female blood	0 04 (0 03–0 06)		
Insulin, plasma	0 8 (after eating)		
Norepinephrine plasma	3 (2–4)		
Oxytocin, blood			1 (USP)
Pitressin, blood			0 01 (antidiuretic)
Progesterone			
Female pregnancy plasma	530 (30–700)		
Female plasma, luteal phase	350 (20–520)		
Protein-bound iodine, plasma	5 (4–8)		
Thyrotropic hormone, blood	·		0 09 (0 05–0 15) (Junkman)
Serotonin (5-hydroxytryptamine)			
Plasma	Traces †		
Platelets	0 26–0 63/mg protein		

* Growth hormone, FSH, intermedin, prolactin, LH (in pregnancy), parathormone, relaxin (in pregnancy) are present *in traces* only

† After administration of reserpine to patient (0 5 μg/ml).

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				20–60
				10–50
Adenosine polyphosphatase	Serum			350–800
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	Serum	Dille units	547	139–219
Catalase	RBC / Plasma	µM/min, acetylcholine hydrolyzed	176 261	
Cholinesterase	RBC / Plasma	µM/min, acetylmethylcholine hydrolyzed	5 8 Traces	
	RBC / Plasma	µM/min, benzoylcholine hydrolyzed	110	
			10	7–14
Cocarboxylase Male / Female	RBC	µg/100 ml (microbiological determination)	6 5 359	5–8 190–520
Dehydropeptidase	Serum		1,390,000	1,320,000–1,500,000
Glyoxalase	RBC			
			19	10–32
Glutamic-oxaloacetic acid transaminase	Serum	Karmen units		
				5–30
Glutamic pyruvic acid transaminase	Serum	Karmen units	36	30–40
Histaminase	WBC / Serum	µg of histamine destroyed in 90 min at 37°C	18 60	0–36 40–80
Lactic dehydrogenase	Serum	Wacker units/min		0–150
Lipase	Serum	ml $N/20$ NaOH needed to neutralize fatty acids freed from standard olive-oil emulsion in 24 hr		
				1–4
Phosphatase Acid	Serum			0–0 5
Prostatic (acid)	Serum			10–13
Alkaline	Serum	mg/hr [illegible] at 37°C at pH 9		50–125
Profibrinolysin	Plasma	Units (One unit will lyse a 0 1 per cent fibrin clot in 2 hr at 28°C at pH 7 2)		

Enzyme inhibitors antistreptolysin (normal range 0 to 100 units), antifibrinolysin (normal range 140 to 163 units)

COAGULATION OF THE BLOOD

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THE CLASSICAL THEORY

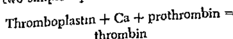
The problem of *hemostasis* is twofold: first, it demands an understanding of the chemistry of the coagulation of blood and, second, it requires a correlation of the data on clotting in a test tube with the physiological process of

TABLE 4-33 ACID-BASE VALUES OF BLOOD AND PLASMA (AT SEA LEVEL)

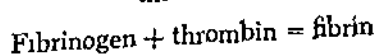
Age and sex	Blood	Hemoglobin: Concentration, mM/liter blood		Hemoglobin: Oxygen saturation per cent		Total CO_2 concentration, mM/liter: Blood		Total CO_2 concentration, mM/liter: Plasma		Plasma pH		Buffer base concentration, mEq/liter blood		CO_2 Pressure, mm Hg		CO_2 Combining power, ml gas/100 ml plasma	
		Value	Range	Value	Range	Value	Range	Value	Range	Value	Range	Value	Range	Value	Range	Value	Range
1-10 Days	C*	10	7 7-12 3	97		18 2	14 8-21 6	22 7	18 3-27	7 42	7 31-7 53	47	41-50	34	27-42		
	V†	10 3		87		19 1		23 6	19 6-28	7 38	7,30-7 46	45	. ..	38	. ..	57	
1-24 Months	V	7 0		67		21 1		24 2	19 2-29	7 38		43	. .	38		50	
6-15 Years	A‡	8 2		97		20		25	22 4-28	7 40	7 33-7.47	46	...	38	29-47		
	V	8 2		67		22 8		27	23 3-30	7 38	7 32-7 44	46	.	43	35-50	57	
16-50 Years male	A	9 0	8 7-10 3	98	95-101	22 2	20 4-24	27	25-29	7 39	7 33-7 45	49	46-52	42	36-47		
	C	9 4	8 4-10 4	97		22 2	19 8-25	27		7 39	7 33-7 45	49	. .	43	35-50		
	V	9 0		67	40-90	24 4	20 6-28	29	24-34	7 35	7 27-7 43	49	. .	49	.	65	56-73
16-50 Years, female	C	7 9	6 7-9 1	97		21 9	19 3-25	26		7 41	7.35-7.47	47		39	31-44		
	V	7 9		63	37-89	23 4		27	23 7-31	7 37	7 31-7 43	48	.	44		61	52-70
Over 50 years male	A	7 7	5 7-9 7	95	59-102	21 5	18 1-25	25		7 42	7 32-7 52	45	.	37	29-45		
	C	8 8	7 4-10 2	96		22 3	20 3-24 3	27		7 39	7 32-7 46	49	.	42	33-50		
Over 50 years, female	A	7 8	6 2-9 4	97	93-101	21 1	17 7-24 5	25		7 42	7 34-7 50	45	. .	36	28-44		

* C capillary blood
† V venous blood
‡ A arterial blood

stanching (See also Part 2, Chap. 28.) In the attempt to find the solution of this problem, the classical theory formulated by Morawitz and by Fuld and Spiro (1904) has been an invaluable guide. The theory can be epitomized by two simple equations:



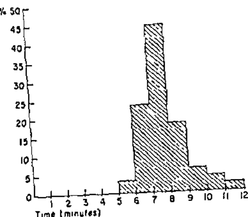
Thromboplastin + Ca + prothrombin = thrombin

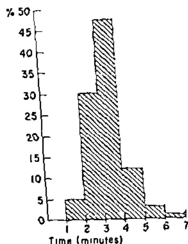


Fibrinogen + thrombin = fibrin

It is now generally accepted that *thrombin* is the key substance upon which hemostasis depends. It is an enzyme converting fibrinogen to fibrin. Its concentration can be measured by the speed with which it clots fibrinogen. If the clotting time is plotted against the concentration of thrombin, a hyperbolic type of curve is obtained with the asymptotes $x = 0$; $y = 0$ This means that, at high dilution of thrombin, the clotting time is infinity and at very high concentration, it is zero In between these limits is a section of the curve which may be designated as crucial In this range the response of the clotting time to increments in the concentration of thrombin is easily measurable The relationship of thrombin to the clotting time has become the basic principle upon which most studies of blood clotting are based.

The most important application of the classical theory was in the development of methods for the determination of *prothrombin.* In the two-stage method (Warner et al, 1934), the oxalated plasma is defibrinated, diluted, and mixed with calcium and thromboplastin. The thrombin generated is measured by the speed with which it clots a standard solution of fibrinogen. In the one-stage method (Quick, 1935, 1936), the clotting time of undiluted oxalated plasma, to which a fixed amount of calcium and an excess of thromboplastin are added, is regarded as the quantitative measure of prothrombin In this method, therefore, the speed of thrombin formation is taken as the measure of prothrombin content. The convertibility of prothrombin is regarded as constant. In the two-stage procedure, speed of conversion is not a factor—it is assumed that, under the conditions of this test, all the prothrombin is converted to thrombin and that the estimation





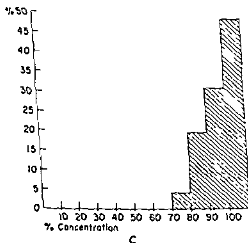


Fig. 4-159. A Clotting time of human blood determined by Lee-White method Distribution of values in 100 normal subjects B Bleeding time determined by Ivy method Distribution of values in 100 normal subjects C. Prothrombin concentration determined by various methods Distribution in 100 normal subjects.

of the total thrombin can be directly translated into prothrombin content.

The diverging principles of these two tests have become the basis of the principal procedures developed for the study of the coagulation of blood. The *two-stage test* is used particularly for the type of study in which an attempt is made to isolate the various clotting factors, and then allowing them to interact in reconstituted systems to form thrombin. No effort is made in such studies to approximate the conditions of equilibrium as they exist in blood. The principle of the *one-stage test* has been adopted for the determination of prothrombin consumption (Quick, 1947), the thromboplastin generation test (Biggs and Douglas), and the partial thromboplastin test (Langdell et al). In the latter group of tests, the convertibility of prothrombin is an important factor and the intact preservation of the composition and state of equilibrium of plasma is essential.

THE PRIMARY CLOTTING FACTORS

According to the classical theory, only three agents are needed for the formation of thrombin, namely, thromboplastin, calcium, and prothrombin. The discovery of a hitherto unrecognized factor (Quick, 1943) which readily disappears from oxalated human plasma on storage and, if decreased in concentration, causes a prolonged prothrombin time, and the report (Owren, 1944) of a patient with a hemorrhagic condition due to a lack of this factor, marked the beginning of a drastic revision of the concept of the coagulation reaction The upheaval of accepted hypotheses was further abetted by the development of the *prothrombin consumption test* (Quick, 1947) By means of this procedure, it could be shown that the thromboplastin activity generated during the clotting of the blood came from the interaction of a platelet factor with a plasma constituent, *thromboplastinogen* (also known as antihemophilic factor or globulin) Later, it was shown that additional factors, particularly PTC (plasma thromboplastin component) were also essential for the formation of plasma thromboplastin (Aggeler et al , Schulman et al.).

Fortunately, it has been possible to incorporate the newly discovered clotting factors into the framework of the well-known existing concept of coagulation by making two revisions in the classical equation of Morawitz, namely, substituting thromboplastin activity and prothrombin complex for thromboplastin and prothrombin, respectively. *Thromboplastin activity* can be regarded as the resultant of the interaction of a platelet factor with thromboplastinogen, PTC, and perhaps other plasma factors. In the *prothrombin complex* are included prothrombin, labile factor, and stable factor. There is good evidence that, in adult human plasma, only about 25 per cent of the prothrombin is in the free or active state. The inactive fraction has been named *prothrombinogen*. During clotting, and also during the storage of plasma in glass, it is all converted to the active state.

In recent years, much progress has been made in partially isolating and purifying the various clotting factors. The first and simplest procedure is high-speed centrifugation. By employing cold and silicone-coated equipment, the platelets can be removed sufficiently to yield an incoagulable plasma. Such plasma clots promptly on the addition not only of platelets, but also of a factor isolated from the erythrocytes (*erythrocytin*).

In the separation of clotting factors, certain adsorbents such as $BaSO_4$ and $Ca_3(PO_4)_2$ have been particularly useful When oxalated plasma is mixed with a small quantity of $Ca_3(PO_4)_2$, the following are completely removed by adsorption prothrombin, prothrombinogen, stable factor, and PTC. These agents can be recovered from the adsorbent by sodium citrate which acts as an eluent. The clotting agents which are not removed by adsorption are labile factor, thromboplastinogen, and fibrinogen. These three factors therefore remain in $Ca_3(PO_4)_2$-treated plasma

During coagulation fibrinogen, thromboplastinogen, and prothrombinogen completely disappear. Other factors, particularly prothrombin and labile factor, are partly consumed. The two clotting agents which are not decreased, and may actually be increased, are stable factor and PTC Serum, therefore, is rich in these two agents; it also contains varying amounts of prothrombin and labile factor, but is entirely devoid of fibrinogen, thromboplastinogen, and prothrombinogen.

Storage of oxalated plasma causes a gradual

diminution of labile factor and thromboplastinogen. *Stored plasma,* therefore, is an excellent medium for assaying labile factor Since all of the prothrombinogen is converted to free prothrombin during storage, the prothrombin time of stored plasma is less than that of fresh plasma, but this is masked by the simultaneous loss of labile factor When an excess of labile factor in the form of deprothrombinized fresh plasma is added to stored plasma, the prothrombin time is 8 to 9 sec, while that of fresh plasma is 12 sec (Quick et al, 1955).

TESTS FOR ESTIMATING COAGULATION AND HEMOSTASIS

Clotting Time. This test should be regarded as suitable mainly for coarse screening of hemorrhagic states When no coagulation occurs, the most likely diagnosis is afibrinogenemia or excessive hyperheparinemia An increased clotting time is found in hemophilia, hemophilia-like states, hypoprothrombinemia, and hyperheparinemia. A normal clotting time is usually observed in thrombocytopenia, stable factor deficiency, pseudohemophilia A, very mild hemophilia, and mild PTC deficiency To obtain reliable results, venous blood obtained by first intention should be clotted under carefully standardized conditions, especially in regard to temperature At 37°C the normal range is 5 to 10 min

Prothrombin Time (One stage Test) The test developed by the author is sensitive and yields a remarkably constant value for normal human plasma 12 ± 0.5 sec When the prothrombin time is increased, it is usually due to a deficiency of prothrombin, stable factor, or both Lack of labile factor also causes a greater value, but clinically this deficiency is relatively infrequent except in severe liver injury Differentiation of the three types of hypoprothrombinemic states is simple Addition of aged serum to the plasma will correct the prothrombin time to normal if stable factor is deficient but will have no effect on labile factor or prothrombin depletion Mixing a small quantity of deprothrombinized rabbit plasma with the plasma to be tested will correct the prothrombin time in labile-factor deficiency but not in the other two types.

The prothrombin time cannot be determined directly on afibrinogenemic plasma since no visible clot can form By mixing such a plasma, however, with an equal volume of deprothrombinized plasma, a satisfactory determination of the prothrombin time can be made In *hyperheparinemia,* the prothrombin time is increased in proportion to like states, the prothrombin time is normal. Therefore, this test is the best and easiest means for differentiating the hypoprothrombinemic states from the hypothromboplastinemias.

The Two-stage Prothrombin Test. Because this procedure is technically difficult to carry out, it is not used extensively in clinical laboratories The claim that this method is more accurate and reliable than the one-stage test has been repeated so often that it has been uncritically accepted by many as established The fallacy of this claim is shown by the fact that, after prolonged *Dicumarol* administration, the prothrombin, as measured by this method, is very low, thus paralleling the results obtained with the one-stage method. Yet, according to most investigators who have used a modified prothrombin-time test, the factor which is most depressed is not prothrombin but stable factor In the newborn infant, the prothrombin, as measured by the two-stage procedure, is only at about 25 per cent of the normal adult level, yet such babies can undergo major surgery without abnormal bleeding provided the prothrombin time is 12 sec Since a bleeding tendency develops in an adult when the prothrombin is reduced to the level of 25 per cent, it is obvious that the prothrombin, as measured by the two-stage method, is not a reliable measure of hemostasis

Prothrombin Consumption Time. This test, which marked a milestone in coagulation studies, is based on the assumption that the amount of prothrombin consumed during clotting is a measure of the amount of thromboplastin produced. The results are valid only if the plasma prothrombin time is 12 sec and the clotting has occurred under carefully standardized conditions.

The thromboplastin produced in plasma is the result of the interaction of a platelet factor with thromboplastinogen, PTC, and perhaps one or more additional plasma constituents. A defective prothrombin consumption, i e, an abnormally short serum prothrombin time, can be due to a deficiency of any one of these factors. The normal range of prothrombin consumption time is 16 to 35 sec. In *thrombocytopenic purpura,* the prothrombin consumption time may be 8 to 14 sec. Usually, this value corresponds to the number of platelets but the quality of the platelets is also a factor. In certain instances, the number of platelets may be normal, but their quality so poor that the prothrombin consumption is very incomplete Such a condition can be designated as thrombasthenia

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In thrombocytopenia, a definite coagulation defect can be demonstrated by means of the prothrombin consumption test, yet, the importance of a vascular factor seems clearly indicated by the increased bleeding time and the positive tourniquet test. In thrombasthenia, a similar situation often exists. In pseudohemophilia A, the vascular factor usually predominates since the bleeding time may be the only abnormal laboratory finding, but in severe cases a clotting defect is often present. In pseudohemophilia B, the coagulation defect is prominent since the prothrombin consumption test is markedly abnormal, but the consistently increased bleeding time is an equally important characteristic of the disease. Interestingly, the coagulation defect can be temporarily corrected by a plasma transfusion, but the bleeding time remains unaltered (Quick, 1957).

The third major class needs no explanation. No abnormality of coagulation can be detected by the available clotting tests. In both scurvy and telangiectasia, the defect is in the anatomical structure of the vessel.

INTRAVASCULAR CLOTTING

The seriousness of excessive bleeding is well recognized but actually the problem is of minor importance compared to that of intravascular clotting which is one of the most important causes of death. It is easy to understand, therefore, why the problem of thrombosis has occupied such an important place in medical research. In spite of much intensive study, the cause of intravascular clotting remains poorly understood, and satisfactory methods for prevention and treatment are still being sought.

Circulating blood remains fluid because all the primary clotting factors are in an inactive state and are not able to interact with each other to form thrombin. It has been fairly widely held that the disintegration of platelets allows the escape of an *active clotting factor* which initiates intravascular clotting, but this is incorrect because mechanically disrupted platelets can be injected intravenously without causing any demonstrable coagulation. The findings in the author's laboratory that erythrocytes contain a potent agent which promptly brings about prothrombin consumption introduces a new facet to the problem of intravascular clotting (Quick et al., 1954), but studies have not been sufficiently completed to warrant any definite conclusions.

Clotting can be initiated by *thromboplastin,* a principle existing in a preformed state in nearly all tissues except the blood. It is present in the walls of blood vessels, and when these are injured enough thromboplastin escapes to allow an incipient clot to form. The thrombin that is generated can not only theoretically clot an unlimited quantity of fibrinogen, but also activate a plasma constituent, thereby bringing about the interaction of the platelet factor with thromboplastinogen and PTC to form plasma thromboplastin. In this manner the autocatalytic mechanism is triggered.

The control of the autocatalytic reaction and the natural protection against thrombosis is still mainly a matter of conjecture. The following theory has been proposed (Quick, 1950). The thrombin which is initially formed is promptly removed by adsorption on fibrin. This prevents the initiation of the autocatalytic reaction. The clot consists of a reticulum of fibrin which offers an immense surface of fibrin to the dispersed serum, thus permitting the prompt removal of thrombin. When clot retraction occurs, the intimate contact of serum and fibrin surface is broken and the thrombin in the serum can then bring about the autocatalytic reaction. This theory has been applied particularly to explain phlebothrombosis.

In the *prevention of thrombosis* many factors have to be considered. Maintenance of a

ranges from 8 to 12 sec and, in PTC deficiency, from 8 to 14 sec. In mild hemophilia the prothrombin consumption time is more sensitive and accurate if carried out on platelet-rich plasma instead of on whole blood. To differentiate true hemophilia from PTC deficiency, aged serum is added to the blood before it is clotted. If the prothrombin consumption time is thereby corrected, the condition is PTC deficiency and not classical hemophilia.

Thromboplastin Generation Test. This test has become a valuable addition to the diagnostic group of procedures for the study of hemorrhagic diseases. It is based on the theory that, when platelets are mixed with plasma adsorbed on $Al(OH)_3$, and serum, all the constituents essential for the formation of thromboplastin are present and will interact quantitatively to form thromboplastin, and that the latter is measured reliably by the one-stage prothrombin-time technique The normal thromboplastin generation time is 8 to 11 sec The platelets provide one clotting component, adsorbed plasma furnishes thromboplastinogen, and serum supplies PTC. If a patient's adsorbed plasma, when mixed with normal platelets and serum, fails to generate a normal amount of thromboplastin, the diagnosis of classical *hemophilia* is suggested. If the condition is *PTC deficiency*, the patient's serum, when mixed with normal platelets and adsorbed plasma, will not produce a normal amount of thromboplastin. The test finds its most important application, therefore, in differentiating classical hemophilia from PTC deficiency

Thrombin Time. The clotting time obtained by mixing a fixed amount of plasma with a standard quantity of thrombin may be designated as the thrombin time. For convenience, a solution of thrombin is chosen of such strength that when 0 1 ml is added to 0 2 ml of normal oxalated plasma, a clotting time of 7 sec is obtained. If the plasma contains heparin, the clotting time will be greatly increased, but if a minute quantity of toluidine blue or protamine sulfate is added to the plasma, the thrombin time becomes normal. The test is useful for the detection and quantitative estimation of heparin in the blood.

Bleeding Time. This test is exceedingly important in the diagnosis and differentiation of hemorrhagic diseases. Normal bleeding time is 2 to 3 min. It is prolonged in acute thrombocytopenia, and occasionally, in thrombasthenia. In pseudohemophilia A, also called *von Willebrand's disease*, it is the one test that generally establishes the diagnosis, since the other procedures, such as the prothrombin time and prothrombin consumption test, usually yield normal results. In the newly discovered disease, *pseudohemophilia B*, a defective consumption of prothrombin is present and the bleeding time is markedly increased. It is the latter finding which clearly differentiates this disease from hemophilia and hemophilia-like states since in these the bleeding time is normal.

THE HEMORRHAGIC DISEASES

Defective hemostasis can result from faulty coagulation (hematostaxis) and from vascular abnormalities (angiostaxis). It is convenient to classify the bleeding states under these two major categories but, practically, it is often found that considerable overlapping occurs and that, in certain states, both factors are operative. As a guide, the following classification is offered.

I. *Bleeding diseases due to clotting dysfunction (hematostaxis)*
  A. *Hypoprothrombinemic states*
    1. Congenital
      a. Hypoprothrombinemia, type I
      b. Hypoprothrombinemia, type II
      c Labile factor deficiency
      d. Stable factor deficiency
    2. Acquired
      a Vitamin K deficiency
      b. Faulty absorption of vitamin K
        (1) Biliary fistula
        (2) Obstructive jaundice
        (3) Sprue
      c Vitamin K antagonists
        (1) Dicumarol and related drugs
      d. Severe liver damage
  B. *Hypothromboplastinemias*
    1 Hemophilia
    2 PTC deficiency
    3. Antithromboplastinogenemia
  C. *Heparinemia*
II *Bleeding diseases due to clotting defect with vascular dysfunction (hematostaxis with angiostaxis)*
  A *Thrombocytopenic purpura*
  B *Thrombasthenia*
  C. *Pseudohemophilia A (von Willebrand's disease)*
  D *Pseudohemophilia B*
III *Bleeding diseases due to vascular abnormality (angiostaxis)*
  A *Physiological dysfunction*
    1 Nonthrombocytopenic purpura
  B *Anatomical defect*
    1. Scurvy
    2 Telangiectasia

The outline is self-explanatory It will be seen that the principal cause of coagulation defects is *lack of primary clotting factors.* Such a lack may come about *congenitally* or may be

acquired The best example of the latter is the hypoprothrombinemia caused by lack of vitamin K. Two important diseases are caused by antagonists The first is antithromboplastinogenemia. In this condition, a substance is present in the blood which neutralizes or inactivates thromboplastinogen, thereby reducing the concentration of this substance to as low a level as occurs in hemophilia The condition, therefore, closely simulates classical hemophilia in nearly all respects except one. It does not respond to blood or plasma transfusions, whereas hemophilia does. In the latter disease, the thromboplastinogen of the donor plasma temporarily corrects the deficiency, whereas in the condition with the circulating anticoagulant, the thromboplastinogen is immediately neutralized. The second antagonist is heparin. Only a few cases in which an excess of this agent has produced a bleeding state are on record (Quick, 1957).

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In the *prevention of thrombosis* many factors have to be considered Maintenance of a

healthy vascular system is of paramount importance, but how to achieve this is still an unanswered question. Good circulation is an important safeguard against venous thrombosis. Altering the coagulability of the blood seems a logical prophylactic measure, but means to accomplish this have only become available during the last decade and a half. Of these agents, *heparin* was the first to be employed. This compound with a cofactor neutralizes thrombin directly and promptly. The second was *Dicumarol*, a compound which was isolated first from spoiled sweet clover hay. It acts as an antivitamin K and suppresses the formation of prothrombin. When the latter is decreased, a bleeding state results. In practice, enough Dicumarol is administered to obtain a prothrombin activity level that affords optimum protection against thrombosis with a minimum danger of hemorrhage. With the use of the *one-stage prothrombin time test*, the optimum level has been found to be about 20 per cent Since Dicumarol has been introduced into therapy, many other compounds have been found that depress prothrombin activity. Several of them are used widely in clinical medicine.

SUMMARY

The coagulation of blood consists of a complex series of reactions, involving at least six compounds which are primary agents needed for the formation of thrombin. For convenience, these can be grouped into two major divisions, the thromboplastinogenic agents and the prothrombin complex. An increased prothrombin time indicates a deficiency in one of the latter group, while a defective prothrombin consumption test suggests a deficiency of one of the thromboplastin-forming compounds By modifications of the two basic tests, the individual clotting factor can be quantitatively determined. As a result of studies based on these tests, a practical classification of the hemorrhagic diseases is made possible. The clotting reactions incorporate an autocatalytic mechanism mediated through thrombin. Normally, the adsorption of thrombin on fibrin appears to be the physiological means whereby the control of intravascular clotting is effected. Clinically, the prevention and treatment of thrombosis are attempted mainly with drugs such as heparin and Dicumarol which either neutralize thrombin directly or suppress its production.

DETERMINATION OF SERUM ENZYMES (TRANSAMINASE AND DEHYDROGENASE)

The transfer of an amino group from an alpha amino acid to an alpha keto acid, thereby forming a new amino acid and a new keto acid, is termed *transamination* (Fig 4-160A) Although there is earlier evidence to suggest such a process, credit for the discovery and first detailed study of transamination belongs to Braunstein and Kritzmann *Aminopherase* is a term applied to the enzymes responsible for transamination, but *transaminase* is the one which is more generally accepted, particularly in the United States This term is a general one and, in order to differentiate between the many transaminase activities which have been demonstrated in a large variety of biological material, a particular transaminase is usually identified by the substrates acted upon Of the large number of different transaminases which exist in plant, animal, and microbial cells, the most widespread and active enzymes are *glutamicoxaloacetic* (GO-T, Fig. 4-160B) and *glutamicpyruvic* (GP-T, Fig 4-160C) *transaminases*.

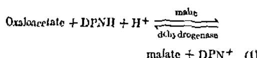
Glutamicoxaloacetic transaminase is widely distributed in animal and human tissues and has been found in all animal and human serums tested. The concentration of this enzyme varies considerably with the various tissues The activity is greatest in heart muscle, followed by skeletal muscle, brain, liver, and kidney in decreasing order Following the destruction of tissue, GO-T is liberated from the cell Because of its high concentration in heart muscle, the amount of GO-T activity liberated following heart-tissue necrosis is sizable and produces a marked rise in the GO-T activity in serum With the recent development of relatively simple methods for the determination of GO-T activity in serum, it has become possible to utilize this value in assessing the presence of acute myocardial infarction in patients.

Since transaminase is an enzyme and does not lend itself readily to direct analysis, its activity is determined by following a measurable chemical entity or reaction. Under the proper conditions the measurable factor is pro-

portional to the enzyme activity and it is possible to translate the results into units of enzyme activity.

Transaminase activity may be measured in a number of ways. Most of these are applications of chromatographic, spectrophotometric, or colorimetric techniques. The chromatographic procedures are beyond the scope of the average hospital laboratory and will not be discussed. However, the spectrophotometric and colorimetric procedures are readily adaptable to routine determinations.

Spectrophotometric Method. Figure 4-160B depicts the reaction involving GO-T. One of the products at equilibrium is oxaloacetate. Malic dehydrogenase, another enzyme, is capable of con- ... of reduced ... to malate ... 'N) in the following manner:



This reaction is accompanied by a change in the optical density at 340 mμ which is proportional to the rate of disappearance of DPNH. At appropriate levels of substrate, enzyme, and DPNH, this rate of disappearance is proportional to transaminase activity. This is the principle of the spectrophotometric procedure of Karmen. The details of a modification of this method (Steinberg et al.), using a relatively inexpensive instrument and commercially available reagents, are given below.

Reagents

1. *0.1 M potassium phosphate buffer, pH 7.4.* Dissolve 13.97 Gm buffer quality anhydrous K_2HPO_4 and 2.69 Gm buffer quality anhydrous KH_2PO_4 in 1 liter of distilled water. Store in the cold.

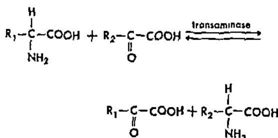
2. *0.2 M l-aspartic acid, sodium salt.* Dissolve 2.662 Gm *l*-aspartic acid in 70 ml of buffer solution 1. Adjust to pH 7.4 (approximately 20 ml 1 *N* NaOH). Dilute to 100 ml with 1. Keep frozen when not in use.

3. *Reduced diphosphopyridine nucleotide (DPNH).* This is available commercially in different degrees of purity. If using 70 per cent pure DPNH, dissolve 10 mg in 10 ml of 1. If using 90 per cent pure DPNH, dissolve 7.5 mg in 10 ml of 1. When diluted 1:10 as in the assay procedure, this solution should give an optical density of about 0.5 at 340 mμ. Keep frozen.

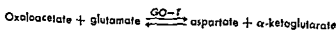
4. *Malic dehydrogenase (MDH).* The enzyme may be prepared from pig heart by the method of Straub. Commercial preparations vary in potency. The enzyme should be diluted so as to contain 800 MDH units/ml. Prepare small amounts as needed. Refrigerate.

5. *0.1 M α-ketoglutaric acid, sodium salt.* Dissolve 1.47 Gm α-ketoglutaric acid in 70 ml of solution 1. The pH is adjusted to 7.4 (approximately 20 ml 1 *N* NaOH). Dilute to 100 ml with solution 1. Keep frozen.

A. General reaction for transamination



B. Glutamic-oxaloacetic transaminase



C. Glutamic-pyruvic transaminase

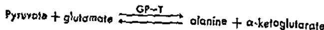


Fig. 4-160. Transaminase reactions.

Procedure. The instrument used is a *Bausch and Lomb Spectronic 20 colorimeter* modified to read at 340 mμ. Any instrument calibrated to measure optical density at 340 mμ may be used. However, the size and shape of the cuvette must be considered in the calculation. This will be illustrated below.

1. For each serum a control as well as an assay tube must be prepared. Add the solution to each as follows:

Reagent	*Control tube, 1*	*Assay tube, 2*
0.2 *M* Aspartate	0.5 ml	0.5 ml
MDH (800 units/ml)	0 1 ml	0 1 ml
DPNH (see above)		0 3 ml
Serum	0 2 ml	0 2 ml
0 1 *M* Phosphate buffer, pH 7 4	2 0 ml	1 7 ml

If because of such factors as lipemia or bilirubinemia, the control tube cannot be balanced at zero, use a smaller volume of serum. Any changes in volume of serum or reagents are compensated by changes in volume of phosphate buffer to keep the final volume at 3 0 ml (after step 3)

2. The contents of the tubes are mixed and allowed to stand for 30 min at room temperature During this time a variable amount of DPNH will be oxidized due to the presence in all serums of some intrinsic dehydrogenase activity together with small amounts of appropriate substrate. In most cases there is ample residual DPNH after this 30-min period but if the optical density has fallen below 0 200 an additional 0 1 ml of DPNH is added Experience with each batch of DPNH will permit one to estimate the proper quantity of DPNH required for step 1

3. After 30 min the tubes are brought to the temperature chosen for the assay Two-tenths milliliter of 0.1 *M* Na α-ketoglutarate is added to each tube and the contents are again thoroughly mixed. If the temperature of the room is fairly steady, the determination may be carried out at room temperature This is quite satisfactory for clinical purposes.

4. Using the control tube as a blank, the optical density of the assay tube is read exactly 2, 4, 6, 10, and 15 min after the addition of Na α-ketoglutarate For serums with low GO-T activity, readings may be taken at 20, 25, and 30 min With serums of high GO-T activity, the change in optical density may become nonlinear before the 15-min reading. To obtain accurate values for such serums, the test should be repeated using less serum or serum diluted with phosphate buffer.

5. From the rate of change in OD_{340}, the GO-T activity of the serum may be calculated.

Calculation. One unit of GO-T activity is the amount of enzyme that will decrease the optical density at 340 mμ at the rate of 0.001/min/cm of light path at 25°C under the conditions described. When the effective light path is not 1 cm, it must be determined. For the Bausch and Lomb ½-in. matched tubes, the effective light path is 0.83 cm.

$$\text{GO-T (u/ml)} = \frac{OD_1 - OD_2}{t_2 - t_1} \times \frac{1}{\text{serum vol, ml}} \times \frac{1}{f_T} \times \frac{1}{f_p} \times 1{,}000$$

where OD_1 = optical density at time t_1
OD_2 = optical density at time t_2
f_T = temperature conversion factor (Table 4-34)
f_p = effective light path (0.83 cm for the Bausch and Lomb Spectronic 20 and ½-in tubes)

Before any observations are accepted for calculation, the linearity of the reaction rate is confirmed by plotting the readings. Instrument instability errors, reading errors, etc., are minimized by using the first and last readings. Usually the 2-min reading does not fall on the straight-line curve and is disregarded. Table 4-34 gives the f_T values for common laboratory temperatures.

The *normal range* for adults is considered to be up to 40 GO-T units/ml of serum. A value of 41-50 units/ml of serum may be classified as borderline with values over 50 units/ml as high (Chinsky et al.). In actual practice a value for serum above 40 units/ml is considered above the normal level. This has been the basis for the utilization of the determination of serum GO-T in myocardial infarction. In cases of acute myocardial infarction the serum GO-T values rise above 40 units/ml usually between 6 and 36 hr after the attack Since the serum GO-T is reproducible in the same individual from day to day, it is conceivable to obtain a value of 40 units of GO-T activity

TABLE 4-34 TEMPERATURE-CONVERSION FACTORS FOR COMMON LABORATORY TEMPERATURES

Temperature, °C	f_T	*Temperature, °C*	f_T
20	0 7	26	1 1
21	0 7	27	1 1
22	0.8	28	1 2
23	0 9	29	1.3
24	0 9	30	1 4
25	1.0	31	1.4

per milliliter of serum which, although elevated for that individual, would not be classified as such according to the division given above. With the accumulation of data, the limit for normal values may be lowered (White).

It is advisable to perform serial determinations in borderline cases. This would not only assist in determining whether there had been an increase in the individual but also would help to differentiate elevations due to liver damage. *High transaminase values following an infarction will reach a peak and return to normal within a week. Liver damage usually results in much higher values over a much more extended period of time* (Wróblewski and LaDue, 1955).

Because the red blood cell concentration of GO-T is many times that of GO-T in serum, it is important that hemolysis be avoided and that the serum be separated from the red blood cells as soon as possible and kept at refrigerator temperature. Refrigerated serums retain essentially all of the GO-T activity for 4 days Freezing [illegible] after an attack [illegible] infarction, it is not essential that the actual determination of GO-T be carried out immediately. Heparin and oxalate do not interfere with the assay, and there does not appear to be any significant difference between the GO-T activities in serum and plasma

Colorimetric Method. By adapting the colorimetric method of Tonhazy et al to the assay of glutamic-oxaloacetic transaminase in tissues, Cabaud and coworkers have been able to measure serum GO-T activity The principle of this method is the determination of oxaloacetate formed in the reaction (Fig 4-160B). The oxalacetate is converted to pyruvate by aniline citrate The dinitrophenylhydrazone of pyruvate is formed, this is extracted and treated with strong alkali to yield a colored compound. The intensity of color, which is measured colorimetrically, is proportional to the level of serum GO-T activity The primary advantage of this method is that it does not require an instrument which is calibrated to read at 340 mμ Since many laboratories may not have such an instrument, the details of the method are given below.

1. Add 0 5 ml of serum and 0 5 ml of distilled water to each of two test tubes

2. At zero time, add to both tubes 0 5 ml of aspartic-ketoglutaric reagent, the substrate for the enzyme. Prepare this reagent as follows dissolve 2 66 Gm *dl*-aspartic acid, 2 00 Gm potassium monobasic phosphate and 0 6 Gm of *a*-ketoglutaric acid in 100 ml of distilled water and adjust the pH to 7 4 with potassium hydroxide.

3. Immediately after the aspartic-ketoglutaric reagent is added, place 1 drop of a solution of trichloroacetic acid (100 Gm/100 ml distilled water) and 1 drop of aniline citrate in one of the test tubes, this will serve as a blank. The aniline citrate is prepared by adding 5 ml of aniline to 5 Gm of citric acid in 5 ml of distilled water.

4. Allow tubes to stand for 20 min at room temperature (approximately 26°C) and add one drop each of trichloroacetic acid and aniline citrate to the second tube.

5. Mix contents and allow to stand for 20 min.

6. To each tube add 0.5 ml dinitrophenylhydrazine reagent, mix contents and allow to stand 5 min (The reagent is prepared by dissolving 100 mg of 2,4-dinitrophenylhydrazine in 20 ml of concentrated hydrochloric acid and 80 ml of distilled water)

7 Add 2 ml of toluene to each tube, shake the tubes vigorously and centrifuge approximately 5 min.

8 Remove 1 ml of toluene from the top layer of each tube and place the aliquots in separate colorimeter tubes.

9 Add 3 ml of an alcoholic solution of potassium hydroxide (2 5 Gm potassium hydroxide in 100 ml 95 per cent ethyl alcohol) to each tube and mix the contents

10. Measure the transmittance in a colorimeter at 490 mμ with the blank set at 100 per cent transmittance The concentration of pyruvic acid may be obtained from a calibration table. From a stock solution of pyruvic acid (1 Gm dissolved in 1 liter distilled water) several dilutions of pyruvic acid containing from 1 to 500 gamma/ml are prepared These are processed as described in the procedure with a blank of distilled water The transmittance of the various solutions are measured and a calibration curve is obtained by plotting on semilogarithmic graph paper the percentage of transmittance against the various concentrations of pyruvic acid

One unit of serum GO-T is defined as the *activity of 1 0 ml of serum that results in the formation of chromogenic material equivalent to 1 gamma of pyruvate under the conditions of the test. These units are only approximately equal to the units obtained by the spectrophotometric procedure*

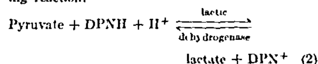
Another colorimetric method measures the quantity of *oxaloacetate* formed directly. Since this compound has a ketone group, it is capable

of reacting with 2,4-dinitrophenylhydrazine to form the colored hydrazone in a manner analogous to the hydrazone formation outlined above with pyruvic acid.

In general, the present colorimetric methods lack specificity and are not as sensitive or accurate as the spectrophotometric method. The latter has the added advantage of measuring the rate of reaction. Thus one can easily determine from the shape of the curve whether there has been an error in the determination. If the curve is not linear, the determination may be repeated with the necessary adjustments. Such errors are not readily detected in the colorimetric procedure where only a single point is selected.

It has already been mentioned that GO-T is found in high concentration in liver tissue and that liver damage may also give elevated serum GO-T values. It appears that GP-T (Fig 4-160C) is present in liver tissee in relatively higher concentration than GO-T whereas the reverse is true for heart tissue *Thus the serum GP-T fails to increase significantly following necrosis resulting from acute myocardial infarction* (Wróblewski and LaDue, 1956)

It may be possible, by following changes in serum GP-T activity, to obtain a more specific serum enzyme indication of hepatocellular damage. Serum GP-T activity may be measured by coupling the reaction in Fig. 4-160C with the following reaction.



$$\text{Pyruvate} + \text{DPNH} + \text{H}^+ \underset{\text{dehydrogenase}}{\overset{\text{lactic}}{\rightleftharpoons}} \text{lactate} + \text{DPN}^+ \quad (2)$$

The change in optical density at 340 mμ is then measured and a calculation similar to the one for GO-T is made.

One of the problems in utilizing the serum GO-T values as an aid in the diagnosis of acute myocardial infarction is the matter of timing Abnormal serum levels of GO-T usually persist only 24 to 72 hr after the infarction occurs. It has recently been reported (White) that serum levels of another enzyme, *lactic dehydrogenase* (LDH), provide a good chemical index of myocardial infarction. The serum levels of LDH remain elevated for periods considerably longer than those of GO-T. Lactic dehydrogenase may be measured in a manner analogous to that used for GO-T. Equation (2) illustrates that reduced diphosphopyridine nucleotide is oxidized to diphosphopyridine nucleotide during the course of the reaction. This is accompanied by the change in optical density at 340 mμ. By following the rate of this change it is possible to determine LDH activity.

SUMMARY

Transaminase may be determined by measuring the appearance of reaction products. This may readily be accomplished by spectrophotometric or colorimetric techniques The instrumental and technical facilities required are simple and available in most clinical laboratories The determinations require small amounts of serum which can be stored either in the frozen state or at 4°C for a few days The only important precaution is the avoidance of hemolysis. Although a Beckmann spectrophotometer is not available to all clinical laboratories, other less expensive instruments are becoming available for the spectrophotometric determination The colorimetric method may be carried out with almost any readily available colorimeter Lactic dehydrogenase activity, which may take on increasing importance in the diagnosis of myocardial infarction, may be measured by utilizing reactions similar to those used to determine transaminase activity.

SEROLOGY AND BACTERIOLOGY

SEROLOGY

The sero-immunologic tests most widely used in the diagnosis and follow-up of cardiovascular diseases fall into two categories. The first encompasses those tests which are immunologically specific. Such tests as the determination of the antistreptolysin titer or the antihyaluronidase titer fall into this category. The second category includes those tests which may give insight into the physiological state of the patient without being specific for any particular causative agent The test for C-reactive protein is in this category.

Specific Tests. The association of streptococcal infection (primarily streptococci of groups A, C, and G) and rheumatic fever has, at the present time, been established beyond

any reasonable doubt. This does not imply that the specific causation or pathogenesis has been elucidated, for causation and association are often not synonymous. However, the development of hypersensitivity to *Streptococcus pyogenes* or to some of its metabolic products has been suggested on the basis of two observed facts:

1. A latent period between the initial streptococcal infection and the subsequent development of rheumatic fever.

2. The presence of various antibodies to streptococci and their metabolic products, with greater frequency, in higher titers, and persisting for longer periods of time, in the rheumatic state than in uncomplicated streptococcal infections.

Because of the correlation between the presence of streptococci and rheumatic fever, most of the specific serological tests are based on the search for antistreptococcal antibodies in the patient's serum

The streptococci comprise a large group of morphologically similar organisms which contain a wide variety of types differing in their metabolic and pathogenic ability (Part 7) The basis for classification, beyond the elementary one of hemolytic ability, is chiefly immunological The basis for group specificity is a polysaccharide, *the C substance*, which divides the streptococci into 14 groups, A, B, C, , N Most of the streptococci pathogenic for humans fall into group A, although some are found in group C as well as in group G These group-specific substances are by themselves nonantigenic but are antigenic in the whole cell The organisms in group A contain, in addition to the group-specific substance, type-specific antigens T, a lipoprotein, and N, probably a protein These type-specific *antigens allow* for further classification of group A streptococci into serological types

In addition to *the hemolysins* (O and S) produced by the organism, it also produces *fibrinolysin* (*streptokinase*) and *hyaluronidase* The host infected with streptococci produces antibodies against all of these factors as well as the somatic protein and polysaccharide molecules Therefore, testing the patient's serum for antibodies directed against one or more of these components serves as an index of whether the patient has had experience, recent or otherwise, with these particular agents Not all of the components are equally potent as antigens, hence certain tests are more delicate indicators than others.

ANTISTREPTOLYSIN TESTS Most of the earliest and best work in this field was contributed by Todd (1932, 1938) who showed that the streptococci produce two types of streptolysin, *streptolysin* O and *streptolysin* S. Streptolysin O (SO) is an oxygen-labile, proteinaceous substance containing sulfur and phosphorus, which has an optimum pH of 6.5 (range 5 to 9), is coagulated by heat, and behaves like a typical protein, being very antigenic. The toxic effect of streptolysin O is very rapid, being observed within minutes after injection into the test animal

Streptolysin S (SS) is an oxygen-stable, markedly heat-labile substance and is produced, so far as the authors know, only by group A streptococci. It is probably a lipoprotein although this may be revised as further information is obtained. There is evidence that streptolysin S is not a single substance but may be a complex of certain labile streptococcal substances combined with serum albumin or nucleic acids *Streptolysin S is most stable* at pH 8. Streptolysin S is much slower in action than streptolysin O, taking longer to lyse red blood cells and also to produce death in test animals One major difference between the two lysins is that SS is not antigenic, or is very weakly so, while SO is very antigenic. That SS must be antigenic is apparent from the observations of SS antibodies in patients' serums. However, attempts to produce antibodies against the lysin have been uniformly unsuccessful. Todd believed that the substance is a full antigen only within the cell In addition, the question of whether serum inhibitors for SS are true antibodies or not, has not as yet been resolved As the significance of SS inhibitors is still in doubt, the only antistreptolysin titers performed routinely are those directed against SO

The *antistreptolysin O* (ASO) test proper is a combination of three components red blood cells, streptolysin, and antistreptolysin One unit of streptolysin O is that amount of streptolysin which will lyse a given number of red blood cells One unit of antistreptolysin is that amount of antiserum which will just neutralize the hemolytic ability of one unit of streptolysin. Hence, *in theory*, the units are based on the lysis of a known

number of RBC's. In practice, however, it is easier to standardize an unknown serum against a sample of antistreptolysin of known potency. An additional advantage of this method is that the hemolytic activity of a given batch of streptolysin does not always correlate with its ability to combine with antibody. To standardize the antistreptolysin O test, it is most accurate to compare the combining powers of an unknown serum with a serum of known titer. The titer of a serum is reported in Todd units (T.U.), the reciprocal of the dilution of serum containing one unit of antistreptolysin. One method of preserving an ASO serum is by globulin fractionation of a serum, or group of serums, known to contain large amounts of antistreptolysin O. The purified globulin is kept as stock antistreptolysin O after standardization against a known ASO serum. For the technique, see Johnson, 1955.

Antistreptolysin O titers are found in normal persons as well as in those with rheumatic fever. Titers below 150 T U. are not considered significant evidence of a recent association of the host with a streptococcal infection. In this test, as in all other serological tests, a rising titer is of more significance than is a stationary one. In practice, the dilutions of serum are carried out in 0 1 log fashion. Therefore, experimental error is confined to within 0.2 log of the differences in titer between two serums. A significant change in titer would thus be any change over 0 2 log dilution.

ANTIHYALURONIDASE TITER. The enzyme hyaluronidase is present in many strains of group A streptococci as well as in certain other organisms. It has the property of being able to depolymerize hyaluronic acid until this substance no longer will give typical coagulation in an acid medium. When hyaluronidase is present in an organism infecting a host, antibodies directed against the enzyme are formed. These antibodies have the ability to neutralize the depolymerizing power of the enzyme. It has been shown that specific neutralizing antibodies are contained in serums from patients recovering from an infection with organisms known to produce hyaluronidase. There is some evidence that these enzymes are group-specific as antigens, for antiserums directed against the hyaluronidase prepared from group A streptococci do not neutralize the enzymatic activity of hyaluronidase prepared from groups C and G streptococci. It had been thought that few group A streptococci produced hyaluronidase. It has been shown, however, that over 30 per cent of group A streptococci produce hyaluronidase, although many do so only to a limited extent.

The test proper for the determination of antihyaluronidase antibodies depends upon the fact that whereas native hyaluronic acid is precipitated into a mucinlike mass in the presence of acetic acid and protein, depolymerized hyaluronic acid gives only a granular precipitate under the same conditions. An antibody directed against hyaluronidase specifically neutralizes the depolymerizing ability of the enzyme. Thus, unknown serums can be titrated against a known amount of hyaluronidase to determine the amount of antihyaluronidase present. Other methods have been described.

The antihyaluronidase titers are relatively lower than the titers obtained using the ASO test. Di Caprio, Rantz, and Randall found that large amounts of streptococcal antihyaluronidase were present in the serum of nearly all subjects with rheumatic fever but the disease may occur in its complete absence. These authors concluded that hyaluronidase was a weaker antigen than streptolysin O.

ANTIDESOXYRIBONUCLEASE TITER. Another test for the detection of streptococcal antibodies was proposed by McCarty (1949), who reported a test for the detection of antibodies directed against streptococcal desoxyribonuclease He found that approximately 50 per cent of 23 patients who had had scarlet fever followed by rheumatic fever showed a significant demonstrable rise in antibody titer against streptococcal desoxyribonuclease. The percentage of patients developing these antibodies, however, seems to be lower than that developing antistreptokinase and ASO antibodies.

For the determination of antidesoxyribonuclease antibodies, the method devised by McCarty may be used. Thus, the basis for this test is that unchanged desoxyribonucleate, when precipitated by alcohol, forms a floating fibrous mass, after this substance has been acted upon by the enzyme, addition of alcohol yields only a fine flocculent precipitate The addition of antidesoxyribonuclease antibodies blocks the action of the enzyme on its substrate, hence an unknown serum may be diluted until a dilution is reached which will just block the action of a given amount of enzyme. This

dilution of serum is taken as one unit and the number of units in the serum is of course the reciprocal of the above-mentioned dilution.

Serial twofold dilution of serum are prepared in broth and 0.25 ml of the dilutions are mixed in 10 by 100-mm pyrex test tubes with 0.25 ml of a solution of streptococcal nuclease containing 2 μ/ml. After 30 min of incubation at 37°C, 0.5 ml of the substrate solution is added to each tube and the incubation continued for another 30 min. One ml of ethyl alcohol is added to each tube at the end of the second incubation, and the tubes are examined for the presence of a fibrous mass. The end point is the highest dilution of the serum which prevents enzymatic degradation of the substrate, so that a definite fibrous mass is formed upon the addition of alcohol. On repetition with other serums, a fourfold change of titer is considered significant. Low dilutions of serum may be heated to 65°C for 30 min to destroy the desoxyribonuclease found in most mammalian serums. This is necessary in dilutions of 1:40 or less.

STREPTOCOCCAL ANTIFIBRINOLYSIN (STREPTOKINASE). Tillett and Garner (1933) described a substance formed by hemolytic streptococci which was able to induce the in vitro liquefaction of human plasma clots. This substance has been found to be an enzyme activator (or kinase) which has the ability to activate a precursor of a protease present in human plasma.

Infection of a host with streptococci producing this kinase results in the production of an immune body having the ability to inhibit the clot-liquefying property of fibrinolysin. This substance, called antistreptokinase, is produced against antigens present in streptococci of groups A, C, and G. For details of the test see Anderson et al. (1948).

At present, there is no clear-cut correlation between the in vitro fibrinolysin, produced by strains of streptococci, and the antifibrinolysin titer of patients harboring the organism, nor is there any indication that the antifibrinolysin titer is correlated with rheumatic fever production.

OTHER ANTIBODIES IN DIAGNOSIS. Weinstein (1953) has reported that, in a series of patients whose serums were tested against an acid-extracted polysaccharide antigen derived from group A streptococci by using a precipitin reaction, the incidence of precipitin for streptococcal carbohydrate was slightly lower in rheumatic fever than in uncomplicated streptococcal pharyngitis. However, precipitating antibody for the antigen was frequently demonstrable in the absence of streptococcal infection, and rheumatic fever could not be ruled out by the absence of this antibody.

Harris (1948) isolated two types of antigenic material from streptococci; these reacted to titers below 1:32 with 91 per cent of normal serums and to titers above 1:32 with 87 per cent of serums from patients with active rheumatic disease. However, he found no correlation between the value of the titer and the degree of clinical activity. More recently, Harris (1955) showed that concentrated supernates from cultures of hemolytic streptococci gave positive complement-fixation reactions with serums of rabbits which had been immunized with living streptococci and with serums of human subjects. There was evidence that this CF antigen was not identical with either the somatic antigens or the extracellular enzyme-antigens.

Nonspecific Tests. C-REACTIVE PROTEIN. C-reactive protein (CRP) is a substance found in the serums of patients undergoing an inflammatory reaction. Patients with noninflammatory diseases characteristically do not contain CRP. The substance was first described by Tillett and Francis (1930) who noted the ability of a substance in the serums of patients with pneumococcal pneumonia to combine with the somatic C polysaccharide of *Diplococcus pneumoniae*. Originally, the reaction was thought to be due to an antibody directed against the polysaccharide antigen. It has since been learned that CRP does not behave like a typical antibody and is found in a wide variety of diseases in which the pneumococcus does not play a causative role. The protein has been purified and characterized by McCleod and Avery. Rabbit antiserums can be prepared against the protein and such antiserums will not react with normal serums. The rabbit anti-CRP incorporated into a simple precipitation test can be used to detect the presence of CRP in an unknown serum. This method is even more sensitive for detecting the presence of the CRP than is the older method of combining an unknown serum with the polysaccharide. The rabbit anti-CRP serum is available commercially in either lyophilized or liquid form.

The appearance or disappearance of CRP in the serum correlates so well with the waxing and waning of the inflammatory process in the host, that this test, while virtually useless for diagnosis, is a sensitive tool in the determination and *evaluation* of an *inflammatory* process.

The test proper is performed using the patient's serum The serum may be secured by venipuncture, but more often enough serum may be collected by micromethods so that venipuncture is not necessary (Goldin and Kaplan, 1955). A capillary tube (1 by 85 mm) is *convenient* to use. The tube is immersed in a small amount of liquid anti-CRP serum and about 20 mm of *antiserum* is allowed to enter the tube by capillary attraction. The tube is then removed from the antiserum and its tip is carefully wiped; then an approximately equal volume of the patient's serum is drawn into the tube by the same procedure. Air must not be allowed to enter the tube and separate the two reagents. The tube is inverted several times and then placed in a block of plasticine or some other convenient holder, and allowed to incubate for two hours at 22 or 37°C. A positive test is indicated by the appearance of a white flocculent precipitate, and a rough quantitative result may be obtained by judging the amount of precipitate.

A complement-fixation test has also been described, in which the CRP in the patient's serum and the rabbit anti-CRP serum combine to fix complement

BLOOD CULTURE TECHNIQUES

The success of blood culture techniques depends on the care and methods used in collecting the blood from the patient, the choice of medium into which the blood is inoculated, and the care with which examination is made during incubation.

Collection of Blood for Culture. The most common method of collection of blood for culture is by venipuncture and the technique is essentially identical with that used for collection of blood samples for serological testing. It is, however, absolutely imperative that strict *asepsis* be observed. The site of entry of the needle must be thoroughly *cleaned* using either 70 per cent alcohol or soap; following this it should be painted with a *suitable* strong antiseptic, preferably 2.5 per cent tincture of iodine. The iodine should be removed with 70 per cent ethyl alcohol and the area allowed *to dry* completely before insertion of the needle. Collection of the blood should be *accomplished* with a sterile, dry syringe and needle. Usually 5 to 10 ml of blood is collected, depending on the number of media to be inoculated.

An alternative to venipuncture has been suggested by Murray and Moosnick (1940) and commented on by Sullivan and Powell (1951). These authors used blood collected by arterial puncture (of either the radial or femoral artery) and reported a higher proportion of positive cultures than *that obtained* in simultaneously collected venous blood cultures.

Inoculation of Blood into Culture Media. After collection, the blood may be handled in one of two ways. One method is to transfer the blood immediately into sterile tubes or flasks containing sodium citrate (0.2 Gm/10 ml of blood). The blood is then sent to the laboratory for inoculation into culture media. The second method is to inoculate the blood into appropriate media at the bedside. This has several advantages. (1) Inoculation directly into the medium reduces the *number* of operations necessary and reduces the dangers of contamination (2) It accomplishes an immediate dilution of antibacterial substances in the blood, whereas the use of an anticoagulant allows for a longer contact between these undiluted substances and any bacteria that may be present. (3) It obviates the possibility that the anticoagulant may inhibit the bacteria which may be present in the blood. (4) It avoids the dangers of long delay in inoculating the blood into the appropriate medium. Once the medium is inoculated, some delay in getting the culture into an incubator is not serious. It should, however, be done as soon as possible

Media for blood culture are many and varied. In general, a suitable medium should be a well-*buffered* infusion (*brain*, brain-heart, soya, etc.) to which 0.1 per cent agar is added. In such a medium, *aerobic* and *microaerophilic bacteria* can be expected to grow well, even though no special attempt is made to reduce oxygen tension. For *anaerobic culture,* fluid thioglycolate medium can be used to advantage It is desirable to add routinely 0.05 Gm of *para-aminobenzoic* acid (PABA) to blood-culture media before sterilization. The PABA antagonizes any sulfa drugs that may be present in the blood specimen and also may act as a growth factor for certain bacteria It is also advisable to use *penicillinase* in the blood culture, but this must be added at the time the culture is made. Directions for its use are included with the vial, it can be obtained from a number of sources. Suitable antagonists for other antibiotics are not available

Blood culture media are usually dispensed in 50- to 100-ml quantities and may be placed in erlenmeyer flasks or, most commonly, in bottles with screw caps. If the blood is to be added directly to

the medium, it is desirable to use a bottle with a vaccine-type cap or rubber washer so that the syringe needle can be inserted and the blood expelled directly into the medium. Numerous suitable arrangements are available. Marwin (1949) has described a blood-culture technique utilizing a bottle in which an agar surface is supplied on one side of the bottle in addition to the usual fluid medium.

The amount of blood used in blood culture is of great importance. The quantity of blood used should never exceed 10 per cent of the volume of medium in the container. If higher concentrations are used, antibodies and other inhibiting factors in the blood may inhibit growth of the bacteria present in the blood. *In low-grade infections (subacute bacterial endocarditis, etc.) it may be desirable to culture 20 to 30 ml of blood, but when this is done, several bottles of medium should be inoculated rather than placing all the blood in one bottle.*

Incubation and Examination of Blood Cultures. *Incubation is carried out at 37°C and all blood cultures should be incubated for at least 21 days before they are discarded as negative.* In the case of certain diseases such as brucellosis, incubation for 42 days is desirable. All cultures should be examined at the end of 24 and 48 hr, first macroscopically for evidence of bacterial growth (cloudiness), and then microscopically and by subculture. Portions of the culture for these examinations should be removed with either a pipette, or syringe and needle to a sterile tube, and then picked up with a bacteriological loop. *Gram stains should be made at 24 and 48 hr regardless of the macroscopic appearance.* The culture should also be streaked on blood-agar plates or other appropriate solid media and examined periodically for the appearance of colonies. Examination from this point on will depend on what organism is suspected.

After the first 48 hr, all negative cultures should be examined at 48-hr intervals for 10 to 14 days and then at weekly intervals until discarded.

There are available from commercial sources specially prepared blood-culture media in bottles from which all air has been excluded. For *anaerobic culture*, it is merely necessary to introduce an appropriate amount of blood and incubate at 37°C. If aerobic culture is desired, one can allow air to enter through a needle covered by a sterile cotton plug. With such bottles, it is also possible to add CO_2 to any desired concentration. The latter is very desirable with certain types of bacterial species.

It is also possible for private laboratories to put up blood-culture bottles in this manner if proper evacuation facilities are available.

I

Catheterization of the heart and large vessels

Right Heart Catheterization
EARL H. WOOD AND H. J. C. SWAN
Left Heart Catheterization
VIKING O. BJÖRK AND G. MALMSTRÖM
Gases in the Blood
CHI KONG LIU
Patterns of Pressure
ALDO A. LUISADA AND CHI KONG LIU
Formulas Used in Cardiac Catheterization
CHI KONG LIU

RIGHT HEART CATHETERIZATION

Catheterization of the right side of the heart gives access to the chambers of the heart and the great vessels, permitting measurement of pressure, the removal of samples of blood and the introduction of substances at desired accessible locations This chapter is concerned primarily with the diagnostic applications of right heart catheterization, although many of the considerations to be discussed have a bearing on the application of this technique to research problems.

Use of any diagnostic technique in medical practice is determined by the value of the information provided by the test in relation to evaluation by simpler methods. At present, the accuracy of diagnosis of cardiac diseases on the basis of history, physical examination, roentgenologic studies, and electrocardiography is impressive. The experienced cardiologist can make an accurate appraisal in the majority of patients who have mitral and aortic valvular disease, patent ductus arteriosus, simple atrial or ventricular septal defects, common atrioventricular canal, isolated pulmonary stenosis, or the tetralogy of Fallot. In clear-cut examples of these malformations, right heart catheterization is not necessary as a diagnostic measure In two groups of patients, however, the procedure is of particular value. One group includes those in whom the diagnosis of organic heart disease has been entertained on the basis of equivocal or uncertain physical signs. In such patients, right heart catheterization may permit the exclusion of dynamically significant heart disease with certainty. The other group includes those patients in whom a complex congenital malformation is present or in whom assessment of the condition of the mitral and aortic valves is not possible on the basis of ordinary clinical examinations.

Each of the groups just mentioned represents a major diagnostic challenge to the cardiologist and it is in these patients that right heart catheterization has its major diagnostic application at present and probably will have in the future. However, accurate diagnosis and assessment of these patients at right heart catheterization necessitate the use of modern equipment that enables the physician to conduct the procedure so that the maximum of relevant information is obtained Of fundamental importance in gaining this objective is the immediate availability to the physician of the information that he is seeking, so that he may alter or extend the study to confirm or exclude the various diagnoses that may appear possible Implicit also in the successful direction of the study is considerable knowledge on the part of the physician of cardiac malformations and the disorders of function that accompany them. It is the authors' opinion that knowledge of the types and variants of congenital and acquired heart disease, familiarity with the data required to establish the presence of these types and their variants, and cognizance of the procedures available to obtain these data are of impoitance equal to or greater than that of the degree of manual dexterity required for the technical performance of diagnostic cardiac catheterization.

It is not sufficient that the physician who undertakes diagnostic cardiac catheterization be sufficiently experienced to reach an accurate diagnosis He must have the equipment necessary to permit him to receive the information relevant to the status of the patient and the circulatory abnormality present as rapidly as possible by means of visual monitoring or direct recorders Also, it is necessary to provide a means to record the data for subsequent study and analysis In this way, the necessity for repeated catheterization or additional diagnostic procedures may be minimized in patients who have complicated diagnostic problems.

PHYSIOLOGICAL VARIABLES DETERMINED DURING CARDIAC CATHETERIZATION

The essential information summarized under the following headings is obtainable with currently available equipment. This equipment should permit continuous visual monitoring of the variables in addition to obtaining permanent records.

Blood Oxygen Content, Saturation, and Tension. Manometric analysis of blood oxygen content by the van Slyke method is not sufficiently rapid for usual diagnostic purposes, therefore, a spectrophotometric method is preferable for measurement of the oxygen saturation of blood obtained by means of a cardiac catheter (Groom et al). The light transmission of hemolyzed blood may be measured in a spectrophotometer and related to the oxygen saturation. Other apparatus includes the Brinkman hemoreflector, which has been used with some success In the authors' laboratory, an oximeter (Wood, 1950) has been used. This instrument has the following advantages. (1) immediate reading on whole flowing blood; (2) small volume of blood used (2 to 5 ml per reading), (3) high relative accuracy (differences in oxygen saturation between successive samples of blood of less than 1 per cent can be detected—Nahas et al), (4) the same instrument can be used to determine indicator substances (blue dyes) in circulating blood and, with modifications in the recording circuit, as a densitometer to detect the presence of a tricarbocyanine dye with a peak absorption of light in the infrared region of the spectrum, and (5) the equipment can be sterilized and the blood is not changed during its passage through the oximeter (This permits the blood to be retransfused into the patient after the determinations have been made) Thus, up to 40 samples of blood may be obtained from a small child weighing no more than 10 lb (4.5 kg) without necessitating transfusion of blood from another source.

Unfavorable features of this instrument include (1) the absence of uniform calibration between instruments in terms of oxygen saturation; (2) low current output, and (3) uncertain life and instability of the barrier-layer photocells

In addition to having a device for the determination of the oxygen saturation of the whole blood withdrawn from the catheter, *it is an advantage to measure continuously the oxygen saturation of arterial blood* This may be achieved by means of an ear oximeter (Wood and Geraci), the use of which safeguards the patient during any procedure, since it enables the operator to be immediately aware of changes in arterial oxygen saturation that may presage a serious change in the patient's status Furthermore, changes in the oxygen saturation of samples of venous blood drawn from the chambers of the heart and great vessels may be evaluated more correctly in relationship to changes in the saturation of arterial blood

Recently developed *miniature* oxygen electrodes

I

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also be of diagnostic value (Lewis et al., 1957)

Selective Indicator-dilution Curves. Arterial indicator-dilution curves are considered in detail in Chap 6. The recording of dilution curves after injection of an indicator at selected points in the cardiovascular system in conjunction with and as a part of cardiac catheterization minimizes the diagnostic errors and is regarded as an essential part of this procedure. Presently available indicators include *radioisotopes* and also *dyes* that absorb light at different regions in the spectrum. Radioisotopes have the disadvantages associated with the use of radioactive materials. Detectors are available for the continuous recording of both isotopic and photometric indicators. Of the latter, Evans blue and indigo carmine, when mixed with plasma, have a peak absorption of about 640 mμ, for which wavelength the red cell of the oximeter[4] and various densitometers[5] have a peak sensitivity. Recently a new dye, namely *cardio green*,[6] with a peak light absorption at 800 mμ has been described and can be detected by the infrared cell of the oximeter or by appropriately designed densitometers[7]

Selective Angiocardiography. In conjunction with cardiac catheterization, the use of selective [illegible]

[illegible] of diatrizoate (Hypaque) sodium or sodium acetrizoate (Urokon sodium) in doses of 0 6 ml/kg body weight may be used, with the possibility of repeating this injection once or more if necessary. Injection is carried out at specific locations within the heart, these are chosen to permit the most pertinent diagnostic information to be obtained *Cinefluorography*, using some form of image amplification or simultaneous biplane rapid film changers, is used to demonstrate the anatomic features of the malformations (Chap 8, Cineradiology) The use of radiopaque materials carries a small but definite risk to the patient, a risk that apparently is substantially greater in patients who have severe cyanotic congenital heart disease, although this is a group in whom the use of these techniques may be most needed

Fluoroscopy. This technique is an indispensable requirement for cardiac catheterization. Additional features must include facilities for obtaining spot films to demonstrate the position of catheters in both anteroposterior and lateral projections. This is best done without *rotating the patient* because of the possibility of movement of the catheter from the desired location during repositioning. Particular care should be taken to safeguard both the laboratory personnel and the patient from the undesirable effects of radiation. *The time of fluoroscopy* for an individual patient should be minimized Times in excess of 10 min are undesirable, *while the maximum permitted in the authors'* laboratory is 20 min.

RECORDING ASSEMBLY

The recording assembly should provide an adequate permanent record of the variables under study as well as visual monitoring of these variables during the procedure Current techniques of cardiac catheterization demand multichanneled recordings on 25-cm or wider paper. At least six channels are required and more are preferable. The deflection of individual channels should not be restricted to a portion of the record. For example, pressure changes of large amplitude should be recorded across the entire width of the paper. The possibility of recording a deflection of large *amplitude is of particular value in relation to* indicator-dilution curves The *speed of the paper* should be adjustable to rates of approximately 1, 5, 25, and 150 mm/sec to cover the ranges in time of the phenomena to be recorded

Direct-writing recorders have the practical advantage of immediate availability of the record However, this is at present outweighed by the narrow paper and the small number of channels available with such recorders. *Photographic recordings* have the major advantage of adaptability, permitting use of a large number of recording channels, the deflections of which may extend to the full width of the *photographic paper* By suitable arrangements of mirrors, a portion of the light beam recording certain important variables may be deflected to permit both visual monitoring and photography of these variables on rapidly developed photosensitive paper[8] (Fig. 4-101)

GENERAL CONDUCT OF THE PROCEDURE

Cardiac catheterization is best conducted by a physician skilled in the technique of the procedure

[4] Manufactured by the Waters Corporation, Medical Instrument Division, Rochester, Minn.

[5] Manufactured by the Colson Corporation, Medical Equipment Division, Elyria, Ohio, or the American Electronics Lab, Inc, Philadelphia

[6] Trade name Indocyanine green, distributed by Hynson, Westcott & Dunning, Baltimore

[7] Manufactured by the Waters Corporation, Rochester, Minn and by the Colson Corporation, Medical Equipment Division, Elyria, or the American Electronics Lab, Inc, Philadelphia

[8] Several types of rapid-developing photokymographs are commercially available from such [illegible] lochester, [illegible], Denver; [illegible] c, Tulsa, [illegible] orporation, Pasadena.

will make it possible to record the oxygen tension of blood flowing through the cardiac chambers or vessels accessible to the catheter tip.

Intracardiac and Intravascular Pressures. Pressure is an important variable of cardiovascular function and is useful for the diagnosis and assessment of the status of various abnormalities. It is necessary to provide for the recording of pressures via the cardiac catheter that may vary from ranges of −10 to 30 mm Hg in one patient to ranges of zero to 300 mm between patients. Because of this wide range of pressures, such equipment should include a two-step (high and low) sensitivity control to record pressures with a deflection of 2 mm on the photographic record per mm Hg and a low sensitivity of 0.5-mm deflection per mm Hg. With these sensitivities, the components of the pressure pulses that are of practical importance usually can be adequately evaluated. Facilities are also necessary to permit recording of pressure in the arterial system from at least two different sites. An appropriate sensitivity of deflection for arterial pressure is a deflection of 0.5 mm/mm Hg

A number of different manometers are currently available Those of the capacitance type require a suitable system of amplification to permit monitoring and recording Strain-gage manometers do not require electronic amplification to drive certain appropriate galvanometers. Until recently, the frequency response of the capacitance type was superior However, currently available strain-gage manometers[1] have a frequency response which approaches that of the capacitance type

The fidelity of reproduction of changes in pressure by the detecting unit is determined in part by its frequency response (Hansen), which is governed by the physical characteristics of all components of the pressure-detecting and recording system, including the needles or catheters used, the manometer itself, and the recording device Ideally, a needle-manometer or catheter-manometer system should have a uniform response throughout its frequency range without appreciable overshoot or resonant characteristics *Underdamped systems* may distort the magnitude of pressure transients at the natural frequency of the detecting system by several hundred per cent *Optimally damped* manometer systems with a uniform frequency response from zero to twelve cycles per second (cps) are, for practical diagnostic purposes, adequate for recording intravascular and intracardiac pressure pulses in human beings (Wood, 1956) Manometers of superior physical characteristics (high natural frequency) allow the use of needles and catheters of small internal diameter The desirability of using the smallest possible needles and catheters needs no emphasis.

Recordings of the intracardiac pressures frequently are distorted by artifacts caused by motions of the catheter generated by the beating heart (Wood et al., 1954). Two solutions to this problem are proposed. One is the use of *a miniature manometer located at the tip of the catheter* (Ellis et al.), which, however, is subject to serious problems owing to difficulties in manufacture and of in vivo calibration. The second solution lies in the use of *a catheter-manometer system with a sharp cutoff in response to frequencies greater than 10 cps.* This system discriminates selectively against pressure artifacts that tend to be of higher frequency and yet permits accurate recording of systolic, diastolic, and mean pressures, and makes available a reasonably accurate version of the contour of the pressure pulse for examination.[2]

Cardiac Rate and Rhythm. *Continuous monitoring of the electrocardiogram* usually is considered essential during right heart catheterization This permits immediate recognition of cardiac irregularities that may develop during the procedure and serves to reduce the hazards associated with arrhythmias The addition of a visually monitored, instantaneous, rate meter (Sturm and Wood) increases the safety of the procedure. Visible display of the electrocardiogram on a cathode-ray oscilloscope allows the physician to interpret changes in the form of the complexes. This type of continuous monitoring can be improved further by the recently developed oscilloscope tube (Memotron tube[3]) that at will can be caused to maintain an image of one or more individual complexes on the face of the instrument for many minutes.

Continuous display of the intracavitary electrocardiogram recorded from an electrode at the tip of the catheter is a valuable aid in localizing the position of the catheter tip and is also of specific diagnostic value in certain conditions such as Ebstein's malformation of the tricuspid valve and anatomically common ventricle

In recent years, miniature microphones have been developed and attached to the tip of special cardiac catheters This makes intracardiac phonocardiography (Part 3, Chap 9, Clinical Phonocardiography), possible, and thus procedure may

[1] Type P23-G, Statham Instruments, Inc , Los Angeles

[2] It should be remembered that an accurate study of the contour of the pressure pulse or of the intracardiac sonic vibrations requires the use of a high frequency strain gage or electromanometer An electric filter may be switched "in" only for the period during which one wishes to avoid the high frequency vibrations. *Editor*

[3] Memotron oscilloscope, manufactured by the Electronics Division of Hughes Products, Inc , Culver City.

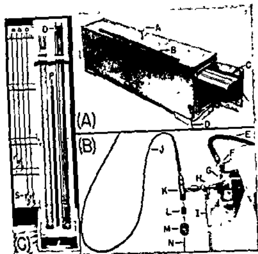


Fig. 4-162. Apparatus used to modify physical characteristics of cardiac catheters to facilitate manipulation of catheter within thorax. A. Thermostatically controlled electric oven utilized for baking catheters to attain the desired degree of stiffness; oven thermostat is adjusted to maintain a temperature of 220°F. *A*, thermometer; *B*, one-meter rule; *C*, cloth-covered board on which catheters are mounted and held straight during baking, *D*, electrical connection. In this picture, the door of the oven is open and the board, holding four catheters, is partially withdrawn Depending on the flaccidity of the catheter, a baking period of 15 min to several hours may be required to produce optimal stiffness of the shaft. B Method used for introduction of stainless-steel stylet into catheter *E*, tubing connecting with pressurized wash bottle for intermittent flushing, via stopcock *F*, of the strain-gage adapter head, *G*, and catheter system with heparinized saline solution. *H*, two-way stopcock for connecting catheter system to strain gage, for pressure recording, and to glass adapter, *I*, connection to cuvette oximeter through which samples of blood are withdrawn for immediate determination of oxygen saturation, per cent, *J*, size 6F cardiac catheter, *K*, adapter assembly incorporated into catheter-manometer system when it becomes necessary to insert stylet in order to stiffen catheter sufficiently to allow manipulation *L*, rubber gasket surrounding stylet, *M*, screw cap to seal stylet in catheter during recording of pressures and withdrawal of samples of blood. *N*, stainless-steel wire 0 4 mm in diameter. The length of the stylet is such that insertion past the catheter tip is impossible The necessity of employing a stylet to stiffen the catheter during manipulation arises infrequently This procedure is used chiefly when the tip of the catheter is in the pulmonary artery and cannot be advanced into the wedge position because of buckling of the catheter shaft in an extremely large right atrium or ventricle. C. Method of sterilizing and storing catheters with maintenance of straight position of catheter shaft *O*, glass tube containing two cardiac catheters undergoing sterilization by immersion in a 1:1,000 aqueous solution of mercuric cyanide for 20 min; *P*, one-meter rule, *R*, wall rack for storing catheters in straight position by suspending them under the tension created by the lucite form, *S*, being used to maintain the desired curvature of the catheter tip.

authors' laboratory without anesthesia in all patients more than 14 years of age and in the majority of those between the ages of 10 and 14. It is the common practice to describe in some detail to patients studied without anesthesia the physical sensations that accompany cardiac catheterization No attempt is made to minimize these and the patient is asked to report any discomfort to the physician. A brief outline of the method has been given to the patient before the procedure commences. This appears to instill a more confident and relaxed attitude in the apprehensive patient as the procedure follows its predicted course and when the sensations experienced generally turn out to be less severe than those described prior to the procedure. Sedatives, consisting of 1.5 gr secobarbital (Seconal) and 0 5 gr *codeine*, are administered when the patient first comes to the laboratory.

For small children and infants, the following regimen has been devised by Lundy to produce a state of amnesia and analgesia Initially, *thiopental (Pentothal) sodium*, 15 mg/lb body weight, is given by the rectal route and a period of 5 to 10 min is allowed for the drug to take effect so that the patient will not remember the intramuscular injections that follow. A single intramuscular injection is given, approximately 10 min after introduction of the *thiopental*, consisting of *levorphan (Levo-dromoran) tartrate* 0 1 mg, *levallorphan (Lorfan) tartrate* 0 1 mg, *promethazine (Phenergan) hydrochloride* 2 0 mg, and *alphaprodine (Nisentil) hydrochloride* 1 0 mg; all these doses indicate the amount given for each 10 lb of body weight. However, the total dose of Levo-dromoran must not exceed 1 mg irrespective of body weight. A period of 20 min is then allowed for analgesia and amnesia to develop, at this time, the site of percutaneous puncture (for introduction of the catheter) or of the incision, if venostomy is required, is infiltrated with a local anesthetic agent. A further quantity of the local anesthetic agent also may be introduced around the artery to be punctured If the child is still restless at this stage of the procedure, another dose of 1.0 mg of Nisentil per 10 lb of body weight may be given intramuscularly This regimen usually allows cardiac catheterization to be accomplished successfully If the procedure exceeds 2 hr, however, further doses of Nisentil of the same size are given at hourly intervals At the conclusion of the

and familiar with the hemodynamics of heart disease. Other members of the team are under the direction of this physician. They include an assistant to manipulate the fluoroscope and the shutters that determine the size of the roentgenographic field, an assistant to take blood samples and to maintain the patency of the various catheters and needles, and a nurse-technician to assist the patient, keep records, and supply instruments and drugs to the physician in charge. In addition, one technician (or more) is needed to maintain and operate the recording equipment and to regulate the detecting devices (Fig. 4-164).

Cardiac catheterization is carried out in the

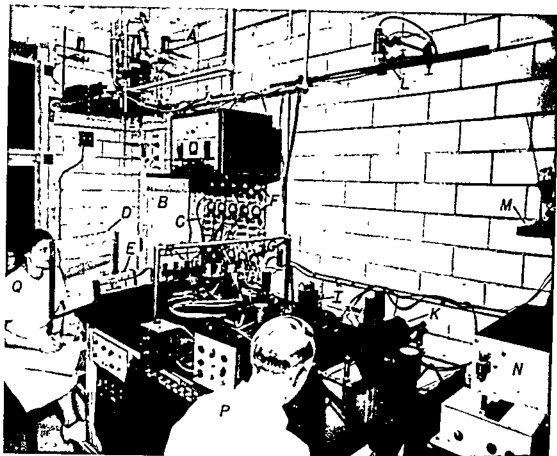


Fig. 4-161. Photokymographic recording room for cardiac catheterization and other diagnostic or investigative studies. Light sources (A) for oximeter galvanometers mounted on shelf (M) Light beams from these galvanometers are reflected by the front-surfaced mirror (E) to the photokymographic (45-cm paper width) camera (N), which runs continuously at a slow speed (1.25 or 5 mm/sec) throughout the procedure. The lower portion of the light beams from the oximeter galvanometers are reflected by the mirror (J) to the ground-glass scale (D), where they are monitored visually by the oximeter operator (Q) The cardiac catheterization is carried out in an adjacent room connected to the recording room by door (B) The electric connections to the catheterization room, consisting of 70 shielded leads, are made via the junction box (C) The meters (F) monitor the voltage supply for each of the 10 strain-gage manometer channels. Similar meters (G) monitor the voltage and amperage for each of the 5 oximeter channels. Parameters of higher frequency, such as the electrocardiogram and vascular pressures, are recorded by means of 14 galvanometers (of geophysical type) mounted on the oscillographic table at (H) and (I). The top portions of the light beams from these and other galvanometers (R) are recorded on the "slow" camera (N), while the bottom portions of the same beams are reflected by the front-surfaced mirror (K) to the "fast" camera (O), which, when turned on by the camera operator (P), records the pressures at paper speeds of 25 or 150 mm/sec as they are being recorded simultaneously on camera (N). A signal is automatically registered on the slow-camera record whenever the "fast" camera (O) is operating. The oximeter operator and camera operator, who visually monitor all variables being recorded from the patient, are in constant communication with the persons in the catheterization room by means of a two-way speaker-microphone assembly.

inserted through the skin, with the aid of analgesia induced by procaine (Novocain) hydrochloride, and is advanced into the selected vein (Fig. 4-163B). The size of the needle required for the introduction of various sizes of catheters is given in Table 4-35.

To preserve the finely sharpened tip of this needle, the skin at the site of insertion is previously punctured with a special stylet Care must be taken to advance the needle so that the entire tip end of the shaft lies within the lumen of the vein, since needles of this large size may permit free recovery of blood when the tip has been introduced only partially into the lumen of the vein. The introducing assembly (Fig 4-163F) is then disconnected from the needle, and the catheter is advanced through the needle into the venous system.

When it is more difficult to puncture veins, as in infants, an incision is made in the skin after procaine analgesia is established. After a suitable vein has been isolated and dissected free, a tie is placed on the distal portion of the vein and a second tie is placed proximally. A small incision is made with scissors between these ties and the catheter is advanced by means of special steel introducers (Fig 4-163C) to facilitate the entry of the catheter into the vein. After catheterization has been completed and the catheter is withdrawn, all ties are removed and hemostasis is obtained by means of an elastic pressure bandage It is unnecessary to ligate the vein, since postcatheterization bleeding has not been a problem Avoidance of ligation of the vein used minimizes the incidence of thrombosis or occlusion in these veins; this is a matter of considerable practical importance because these patients frequently may have to undergo further study and operation The catheter is connected by means of a two-way stopcock to a strain-gage manometer, to a side arm of which is attached a source of high pressure suitable for flushing small quantities of sterile Ringer's solution through the catheter to maintain its patency The second arm of the two-way stopcock is connected to a cuvette oximeter by means of which the oxygen saturation of samples of blood may be determined.

Calibration of Pressure Manometers. The reference or zero level used as a base line for measurement of pressure in this laboratory is at the midthorax at the level of the sternal end of the 3d interspace (Pollack and Wood) This reference position is established at the beginning of the procedure. For purposes of calibration, the pressurized wash bottle used to flush the manometer systems to maintain patency of the catheters and needles is used in conjunction with its attached pressure bulb and mercury manometer to attain appropriate standardizing or calibration pressures (Fig. 4-164, J and K). For each calibration of these manometer systems, the meniscus of the wash bottle is adjusted by means of a rack-and-pinion gear assembly to the midthoracic level, this point having been established previously and adhered to in relation to the position of the patient irrespective of the position of the manometers, which, however, must be recalibrated if their position is changed With atmospheric pressure operative on the surface of the fluid in this wash bottle, a zero calibration is recorded by opening the flush valve of each manometer system simultaneously to this zero pressure in the wash bottle. Other standard pressures (calibration values) appropriate to the manometer system and pressure values under study are recorded by adjusting the pressure in the pneumatic pressure system of the wash bottle to appropriate levels by means of the mercury manometer and pressure bulb, in turn, a recording is made of the deflections presented by each of the manometer systems when they are simultaneously subjected to each of these selected pressure levels by the opening of their respective flush valves to the wash-bottle system.

ing taken to round off the edge of the back portion of the bevel so that the possibility of cutting the catheter during manipulation through the needle is minimized.

TABLE 4-35. SIZE OF NEEDLES REQUIRED TO INTRODUCE VARIOUS CARDIAC CATHETERS

Size of catheter	*External gage of needle* *
4F	16
5F	15
6F	13
7F	12

* These special needles and stylets can be obtained from T. L. Martin, Rochester, Minnesota.

RIGHT HEART CATHETERIZATION OF A PERSON IN WHOM NO CARDIOVASCULAR ABNORMALITY IS DEMONSTRATED

The incidence of errors of omission or commission in diagnostic cardiac catheterization is minimized if, as far as possible, all procedures are carried out in an orderly sequence, beginning with collection of complete data regarding the status of pressures and blood oxygen saturation at the level of the right atrium and great veins This information then serves as the foundation on which the structure of data collected in the subsequent portions of the

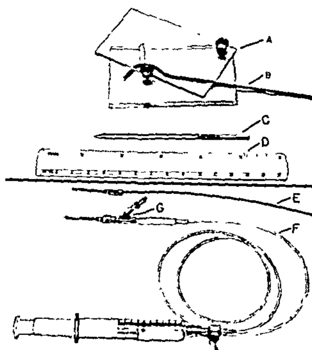


Fig. 4-163. *Mechanical aids for facilitating introduction of cardiac catheter into peripheral vein. A, lucite form for shaping curve of catheter tip; B, size 6F cardiac catheter with tip in place in form; C, instrument to aid in introduction of tip of catheter through an incision in the vein wall (designed by Dr. J. W. Pender); D, rule (15 cm); E, size 6F cardiac catheter threaded through a size 13T hypodermic needle utilized to introduce the catheter through the skin and overlying tissue into the vein without incision; F, apparatus used for venipuncture preparatory for introduction of catheter, the plastic tubing, syringe, and needle are filled with sterile heparinized saline solution; G, side-arm hypodermic adapter that provides a convenient finger hold during puncture of the skin and vein. During venipuncture, the syringe and stopcock are operated by an assistant. When the vein is entered, the lumen of the needle can be kept patent and its continuity with the lumen of the vein readily checked by intermittent flushing with saline. The needle is then disconnected from the metal adapter and the catheter is inserted through the needle into the vein and advanced on into the thorax This technique has been used in more than 75 per cent of the cardiac catheterizations done in the authors' laboratory during recent years.*

procedure and before the cardiac catheter has been removed from the vein, a stimulant is given, via the catheter, consisting of β,β-methylethylglutarimide (*Megimide*) 10 mg and *amphenazole* (*Daptazole*) 30 mg without relation to body weight. If the patient is not responsive after this medication, 5 min are allowed to elapse and the same dose is again given intramuscularly. In most instances, a state is attained that resembles normal sleep, lasts for 1 to 2 hr, and from which the patient can be aroused easily.

The cardiac catheters[9] used in the authors' laboratory are made of *smooth-bore nylon with a* woven nylon covering and bird's-eye tips, they range in diameter from 4F to 7F and in lengths from 50 to 130 cm. These catheters are always maintained in a straight position during storage and sterilization. They may be stiffened, if required, by baking them in a straight position in a special oven at approximately 100°C for 20 min (Fig. 4-162A). The catheters are stored by hanging them from the hub with the tip held in a curved position by a plastic mold (Fig. 4-162C). When required for use, the selected catheters are sterilized by immersion in a 1:1,000 solution of mercuric cyanide for 20 min, during this time coiling of the catheter shafts is also avoided. They are removed from the sterilizing solution by the assistant and washed clean with a sterile isotonic solution of sodium chloride by the physician immediately prior to their use. Occasionally, when manipulation is hampered, by undue flexibility of the catheter or by venospasm, a wire stylet is introduced into the catheter to increase its stiffness (Fig. 4-162B).

A vein in the antecubital fossa of the right arm is usually selected in the authors' laboratory as the most favorable position from which to carry out cardiac catheterization because of the greater facility with which the catheter may be made to enter the inferior vena cava and the pulmonary artery from the right atrium With a tourniquet on the upper part of the arm, both medial and lateral veins in the antecubital fossa are palpated. The medial vein is preferred, however, if the medial vein is not easily accessible and a well-developed lateral vein is present, this vein may be used, although difficulties due to venospasm are more frequent when it is employed. Direct percutaneous puncture with special needles is used, in most adult patients and in many children, for insertion of the catheter into the vein (Wood, 1953) A cut-down procedure is usually necessary in infants and in certain adult patients who have small or obscure veins or whose superficial veins have been utilized for previous diagnostic or therapeutic procedures For percutaneous introduction, a special thin-walled needle[10] of suitable size is

[9] Manufactured by the United States Catheter Co, Glens Falls, New York.

[10] Special thin-walled tubing is used to fabricate these needles The internal surface of the shaft is polished by hand by working the needle over suitably sized lengths of cord inserted through the shaft and impregnated with a grinding compound The tip of each needle is ground by hand under a binocular microscope, particular care be-

inserted through the skin, with the aid of analgesia induced by procaine (Novocain) hydrochloride, and is advanced into the selected vein (Fig. 4-163B). The size of the needle required for the introduction of various sizes of catheters is given in Table 4-35.

To preserve the finely sharpened tip of this needle, the skin at the site of insertion is previously punctured with a special stylet. Care must be taken to advance the needle so that the entire tip end of the shaft lies within the lumen of the vein, since needles of this large size may permit free recovery of blood when the tip has been introduced only partially into the lumen of the vein The introducing assembly (Fig. 4-163F) is then disconnected from the needle, and the catheter is advanced through the needle into the venous system.

When it is more difficult to puncture veins, as in infants, an incision is made in the skin after procaine analgesia is established. After a suitable vein has been isolated and dissected free, a tie is placed on the distal portion of the vein and a second tie is placed proximally. A small incision is made with scissors between these ties and the catheter is advanced by means of special steel introducers (Fig 4-163C) to facilitate the entry of the catheter into the vein. After catheterization has been completed and the catheter is withdrawn, all ties are removed and hemostasis is obtained by means of an elastic pressure bandage It is unnecessary to ligate the vein, since postcatheterization bleeding has not been a problem Avoidance of ligation of the vein used minimizes the incidence of thrombosis or occlusion in these veins, this is a matter of considerable practical importance because these patients frequently may have to undergo further study and operation. The catheter is connected by means of a two-way stopcock to a strain-gage manometer, to a side arm of which is attached a source of high pressure suitable for flushing small quantities of sterile Ringer's solution through the catheter to maintain its patency The second arm of the two-way stopcock is connected to a cuvette oximeter by means of which the oxygen saturation of samples of blood may be determined

Calibration of Pressure Manometers The reference or zero level used as a base line for measurement of pressure in this laboratory is at the midthorax at the level of the sternal end of the 3d interspace (Pollack and Wood) This reference position is established at the beginning of the procedure. For purposes of calibration, the pressurized wash bottle used to flush the manometer systems to maintain patency of the catheters and needles is used in conjunction with its attached pressure bulb and mercury manometer to attain appropriate standardizing or calibration pressures (Fig 4-164, J and K). For each calibration of these manometer systems, the meniscus of the wash bottle is adjusted by means of a rack-and-pinion gear assembly to the midthoracic level, this point having been established previously and adhered to in relation to the position of the patient irrespective of the position of the manometers, which, however, must be recalibrated if their position is changed. With atmospheric pressure operative on the surface of the fluid in this wash bottle, a zero calibration is recorded by opening the flush valve of each manometer system simultaneously to this zero pressure in the wash bottle Other standard pressures (calibration values) appropriate to the manometer system and pressure values under study are recorded by adjusting the pressure in the pneumatic pressure system of the wash bottle to appropriate levels by means of the mercury manometer and pressure bulb, in turn, a recording is made of the deflections presented by each of the manometer systems when they are simultaneously subjected to each of these selected pressure levels by the opening of their respective flush valves to the wash-bottle system

TABLE 4-35 SIZE OF NEEDLES REQUIRED TO INTRODUCE VARIOUS CARDIAC CATHETERS

Size of catheter	*External gage of needle* *
4F	16
5F	15
6F	13
7F	12

* These special needles and stylets can be obtained from T L. Martin, Rochester, Minnesota.

RIGHT HEART CATHETERIZATION OF A PERSON IN WHOM NO CARDIOVASCULAR ABNORMALITY IS DEMONSTRATED

The incidence of errors of omission or commission in diagnostic cardiac catheterization is minimized if, as far as possible, all procedures are carried out in an orderly sequence, beginning with collection of complete data regarding the status of pressures and blood oxygen saturation at the level of the right atrium and great veins This information then serves as the foundation on which the structure of data collected in the subsequent portions of the

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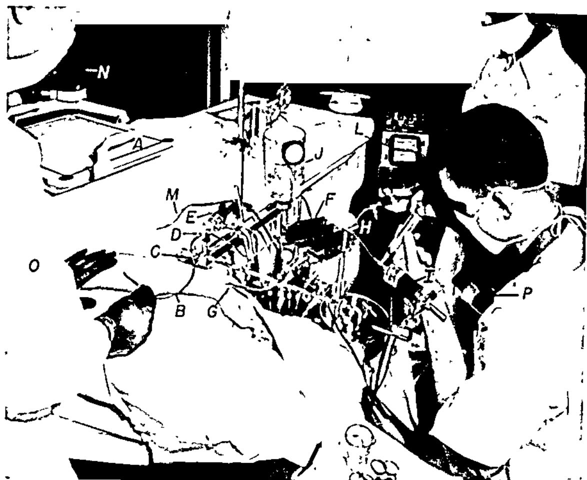


Fig. 4-164. Transducer assembly used for cardiac catheterization. *A*, fluoroscopic screen operated by assistant *N* for viewing catheter *B* as it is manipulated by physician O and x-ray plate holder for subsequent roentgenographic verification of catheter position. The catheter has been introduced percutaneously via the needle *C*, which subsequently has been withdrawn to the external end of the catheter shaft The catheter can be connected by the two-way stopcock *D* either to the strain-gage manometer *E* for recording of intracardiac pressures or to the cuvette oximeter *F* during withdrawal of blood samples for immediate and continuous photometric analysis of blood oxygen saturation or the concentration of indicator dyes. The needle G in the radial artery is connected to a second cuvette oximeter; *H*, strain-gage, *I*, assembly for immediately interchangeable measurement of systemic arterial pressure, arterial oxygen saturation, or indicator-dilution curves The pressurized wash bottle *J* containing sterile heparinized Ringer's solution is used for frequent intermittent flushing of the catheter and arterial needle-manometer systems to maintain their patency. The fluid level in the wash bottle is adjusted to the midthoracic level by the rack-and-pinion gear *K* and serves as the zero reference point for the manometer systems, which are calibrated simultaneously by recording the deflections produced by known pressures (mercury manometer) in this wash-bottle system *L*, twin-tube oscilloscope for continuous display of intracardiac pressures being transmitted by the catheter and the electrocardiogram, picked up by thoracic leads *M*. The chest microphone *P* worn by the first assistant is connected to a recorder into which the time and nature of the various steps in the procedure are dictated as they occur. This protocol is transcribed after the procedure is completed and is then used for identification and synchronization in the subsequent analysis of photokymographic records and other data collected during the procedure. This figure illustrates the simultaneous withdrawal of blood from the pulmonary artery (via the catheter) and the radial artery for subsequent manometric analysis of gas content for determination of pulmonary blood flow by the direct Fick method The rate of oxygen uptake and carbon dioxide elimination is determined simultaneously.

procedure is built in order to obtain a complete picture of the situation in a given patient. This orderly sequence of cardiac catheterization can be best illustrated by a description of a catheterization procedure as it would be done in a person in whom abnormal findings were not encountered and in whom the presence of an apparently normal cardiovascular system was established. Possible alterations in the conduct of the procedure when pathologic changes are encountered at various levels in the heart will be discussed below. If possible, information concerning pressure and blood-oxygen saturation values at each level of the heart is collected in sequence, starting with the great veins and right atrium, and then passing to the right ventricle, the pulmonary-artery wedge position, and the pulmonary artery, *successively. The values for intracardiac* and great-vessel pressures and blood oxygen saturations encountered in normal persons (Barratt-Boyes and Wood) are summarized in Table 4-36 In addition to the *average values*, the so-called *95 per cent confidence limits* are also given

In practice, the catheter is advanced from a vein in the forearm, and its tip is positioned in either the right ventricle or the inferior vena cava just below the diaphragm A series of blood samples is analyzed for oxygen saturation in rapid succession by withdrawal of blood via the catheter through the cuvette oximeter from the right ventricle, the midportion of the right atrium, high in the right atrium, and the superior vena cava, or from the inferior vena cava, the midportion of the right atrium, high in the right atrium, and the superior vena cava, as the tip of the catheter is withdrawn to these positions in rapid sequence.

Values substantially different from those given in Table 4-36 raise the question of significant hemodynamic abnormalities. In normal persons, the maximum pressure in the right atrium is usually that of the A wave; for practical purposes, the superior and inferior caval pressures and pulse contours are not significantly different from those of the atrium. It is important to recognize that the oxygen saturation of superior caval blood in unanesthetized patients is usually less by approximately 6 per cent than the saturation of blood withdrawn from the inferior vena cava. In order to be certain as to the presence or absence of "arterialization" at the right atrial level, that is, a significant increase in the oxygen saturation of right atrial blood in relation to caval blood, it is the practice to withdraw several series of blood samples in fairly rapid succession from the inferior vena cava, the right atrium, and the superior vena cava. *An unusually low satu-*

TABLE 4-36 VALUES OF BLOOD OXYGEN SATURATION AND PRESSURE IN HEART AND GREAT VESSELS OF NORMAL PERSONS

Location	*Blood oxygen saturation, per cent*		*Pressure, mm Hg*	
	Average	*95% Confidence limit ± (2 SD)*	*Average*	*95% Confidence limit ± (2 SD)*
Brachial vein			8	5
Inferior vena cava	83	10	9/4	5/5
Right atrium	80	6	9/4	6/6
Mean			8	5
Superior vena cava	77	10	9/4	5/5
Right ventricle	79	4	27/4–10	8/6
Pulmonary artery	78	5	22/12	8/6
Pulmonary-artery wedge	98 *	5	15/9	6/5
Mean			12	4
Radial artery	97 5	2	135/71	31/15
Mean			91	17

* It was possible to withdraw blood samples from the wedge position in only 66 per cent of the persons studied

ration of inferior caval blood in relation to the superior vena cava may be due to sampling in error from the hepatic vein instead of the inferior vena cava itself; in such circumstances, real effort must be made to obtain an adequately representative series of samples. When the question of arterialization at the level of *the right atrium has been excluded with certainty*, it is then appropriate to advance the catheter through the tricuspid valve in order to record pressure from the lower part of the right ventricle and to establish the presence or absence of arterialization across the tricuspid valve This is done by rapid consecutive analyses of the oxygen saturation of blood withdrawn in succession from the two sides of the tricuspid valve. Since nonrepresentative sampling of right atrial and right ventricular blood is not uncommon, it is the usual practice to withdraw several consecutive pairs of samples from the lower part of the right ventricle and the right atrium to include or exclude with the highest possible degree of certainty the presence of arterialization in the lower part of the right ventricle. In this process, several continuous tracings of pressure using an instrument of high sensitivity (2-mm deflection per mm Hg) should be obtained during withdrawal of the tip of the catheter across the tricuspid valve in order to obtain data pertaining to the function and position of this valve

It is then appropriate to attempt to advance the catheter through the right ventricle and into the pulmonary artery This can be achieved best in most instances by causing the catheter to loop into approximately a semicircle in the right atrium. The catheter is left in this position for about one minute to allow the distal portion of the shaft to take a set in this position The catheter is then manipulated so that the tip faces medially in the lower portion of the right atrium, in which position it usually will pass through the tricuspid valve When the valve is traversed, the catheter usually can be advanced rapidly into the pulmonary artery. In practice, it is best to advance the catheter directly into the wedge position in the pulmonary artery, since delay at this stage may render the subsequent process of wedging the catheter in a small pulmonary artery more difficult. A valid pulmonary-artery wedge pressure can be identified by the following findings. (1) The pressure is significantly less than is pulmonary arterial pressure. (2) The contour of the pulse is significantly different from that of pulmonary arterial pressure. (3) Blood highly saturated with oxygen (98 per cent) usually is obtained from this wedge position. (4) When the catheter tip is withdrawn from the wedge position, fluoroscopy reveals a sudden snap as it is freed from this position, so that the catheter passes rapidly back into a main pulmonary artery as if it were suddenly released from a tight grip. In normal persons, the peak pressure in the pulmonary-artery wedge contour is usually that of the V wave. However, the maximal V wave in the authors' studies on normal resting persons has not exceeded 21 mm of mercury.

It is the practice in the authors' laboratory to obtain pulmonary-artery wedge pressures from several locations in the same lung or in both lungs, because of some degree of variability between pulmonary-artery wedge pressure contours that may reflect different degrees of damping of the left atrial pressure pulse, which these contours unquestionably represent. The catheter is withdrawn from the wedge position to the main pulmonary artery, and the oxygen saturation of blood in the pulmonary artery is then determined by means of the cuvette oximeter. The oxygen saturation of this sample should be closely similar to that of right atrial or right ventricular blood. If this is not the case, then a series of samples is drawn in rapid succession from the pulmonary artery and the outflow portion of the right ventricle to ascertain the presence or absence of arterialization at the level of the pulmonary artery. It is unusual for the oxygen saturation of samples of blood withdrawn from these sites to differ by more than 2 per cent in the absence of an aortopulmonary left-to-right shunt. In this process, several continuous pressure recordings should be obtained during careful slow withdrawal of the catheter tip across the pulmonary valve in order to obtain data pertaining to the function and position of this valve. *The systolic gradient across the pulmonary valve averages 2 mm Hg in normal persons and has not been found to exceed 7 mm.* The pressure gradient across the pulmonary valve should be determined only on records that are free from possible artifacts due to the irregularities of the heart beat that are associated with cardiac arrhythmias and

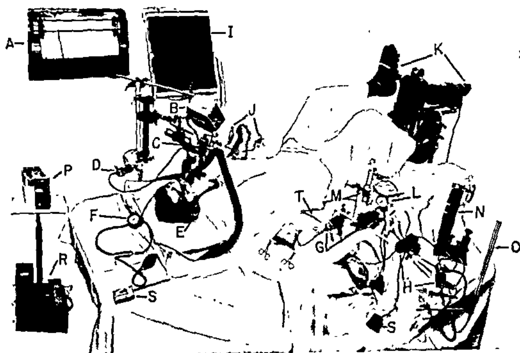


Fig 4-165. Assembled apparatus for determination of ca diac output by the direct Fick or dye-dilution methods and recording of right heart and systemic arterial pressures during rest and exercise A, direct-writing instrument for recording consumption of oxygen and other ventilatory variables from a closed-circuit spirometer system, B, tachometer indicating rpm of bicycle ergometer, C, mouthpiece, tubing connections, and change-over valve to spirometer system; D, strain gage recording changes in respiratory pressure in oral airway; E, ear oximeter; F, manometer–hand-bulb assembly for inflation of pressure capsule in ear oximeter; G, strain-gage-manometer–cuvette-oximeter assembly for recording pressure, oxygen-saturation, or dye-dilution curves in blood withdrawn from cardiac catheters, H, strain-gage-manometer–cuvette-oximeter assembly for recording systemic arterial-pressure, oxygen-saturation, and dye-dilution curves, I, roentgenoscopic screen and x-ray film holder for recording position of catheter tip; J, assembly for rapid injection and flushing of dye into antecubital vein. K, bicycle ergometer with tachometer dynamo attached, L, wash bottle containing sterile heparinized Ringer's solution under pressure, used as zero reference point in calibration of manometers and for flushing catheter, arterial needle, and cuvette oximeters, M, reference marker for midthoracic level and ratchet mechanism for adjusting height of wash-bottle meniscus to midthoracic level during simultaneous calibrations of manometer systems in situ, N, screw control mechanism and mercury manometer for regulating and indicating pressure in reference wash bottle during simultaneous calibration of strain-gage manometers, O, buret for indicating rate of blood flow through the cuvette oximeter during recording of arterial dye-dilution curves, S, signal switches for recording the instant of dye injection and marking each milliliter of blood flow through the cuvette oximeter. T, leads for recording electrocardiogram and heart rate by means of an instantaneous cardiotachometer; P, twin-tube oscilloscope for continuous monitoring of electrocardiogram and pressure pulses being transmitted through the catheter simultaneously with photokymographic recording of these and other physiological variables under study, R, strain-gage amplifier and isolation unit for amplifying output of catheter strain gage G for display on the oscilloscope simultaneously with direct-current operation (i e, without electronic amplification) of suitable recording oscillographic galvanometers The various physiological variables under study are visually monitored and recorded continuously in an adjacent room by means of the photokymographic recording assembly shown in Fig 4-161

are continuous, showing the pressure both above and just below the pulmonary valve during one or more complete respiratory cycles.

When this information has been obtained and its interpretation is clear, the catheter is placed in the main pulmonary artery or one of its principal branches. A needle is then inserted into a peripheral systemic artery and the oxygen consumption is measured by the open-circuit method. The radial artery is usually selected, since puncture of this artery is least disturbing to the patient and permits convenient arrangement of equipment on the same side of the table as for sampling blood from the venous catheter (Figs. 4-164, 165, and 166). It also leaves one arm of the patient free, which is of importance to his peace of mind and personal comfort. The radial artery can usually be punctured, even in small infants. When this puncture fails in the latter group, recourse occasionally may be had to puncture of the femoral artery. Several arm boards (of various sizes) that fix the hand in a dorsiflexed position are available (Fig. 4-166). Puncture of the radial artery is performed after infiltration of the puncture site in the skin and the region of the artery with a 2 per cent solution of *procaine*. A standard 20-gage hypodermic needle is used for this puncture; it is internally polished and its tip is sharpened by hand under a binocular microscope. The oxygen consumption is then determined by the open-circuit method, and blood samples are obtained simultaneously from the pulmonary and radial

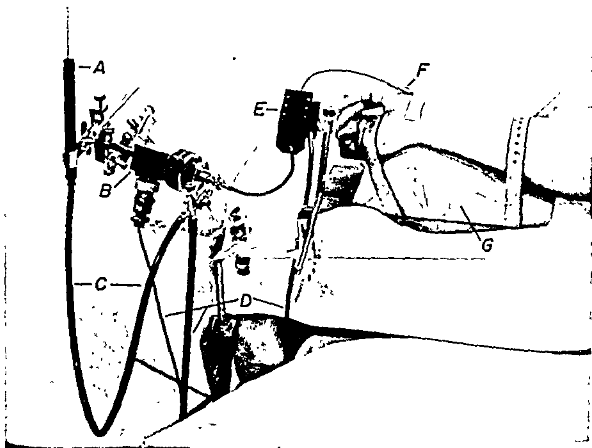


Fig. 4-166. Cuvette-oximeter sampling system for immediately interchangeable continuous recording of arterial pressure, arterial oxygen saturation, or the concentration of indicator dyes. An indwelling needle in the right radial artery F is connected to a strain-gage manometer B by a cuvette-oximeter–tubing system E via 2 two-way stopcocks that enable blood to be drawn through plastic tubing C into a buret A for measurement of the rate of blood flow through the system during recording of dye-dilution curves, or that allow connection of the system to the strain gage for recording arterial pressure. Electric leads D from the cuvette oximeter and strain-gage manometer lead to the photokymographic recording assembly in an adjacent room (Fig. 4-161). The special arm board G fixes the hand and forearm with the wrist in the dorsiflexed position to facilitate puncture of the radial artery.

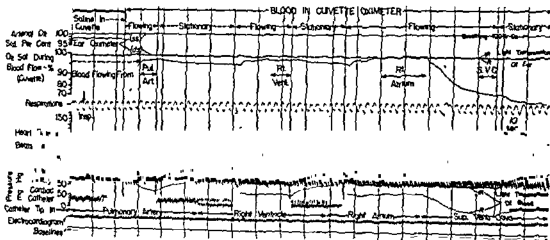


Fig 4-167. Segment of a photokymographic recording routinely recorded continuously throughout *right heart catheterization* by the "slow" camera. (See Fig. 4-161 for explanation) This segment shows intracardiac and arterial pressures and the oxygen saturation of *blood samples* being withdrawn in rapid succession from different levels in the *heart as the tip of a cardiac catheter* was withdrawn in *successive steps from the pulmonary artery* to the right ventricle, then to the *right atrium, and* then to the superior vena cava in a patient with an atrial septal defect, mitral stenosis, and *atrial fibrillation*. The arterial oxygen saturation (ear oximeter), respiration, instantaneous *heart rate, electrocardiogram*, and the transmission of red and infrared light *(double-scale oximetry) of the ear* and the *blood withdrawn from the catheter are also recorded. The vertical black lines extending the full* height of the paper delineate 10-sec intervals and were 5 cm apart on the original *record. IR and R* indicate the recordings of the transmission of infrared and red light by the ear and the blood, *respectively*. The patient was breathing 99.5 per cent oxygen, so that the arterial oxygen saturation was constant at 100 per cent. *Determinations of the oxygen saturation of* blood *by the cuvette oximeter are usually read off only during* the actual period of withdrawal *of the* blood samples through the cuvette. These periods are delineated by the double-headed arrows labeled *pulmonary artery, right ventricle, right atrium,* and S.V.C. (superior vena cava), *respectively*. During withdrawal of the catheter tip across the pulmonary and tricuspid valves *and from* the right atrium, an additional continuous recording is obtained simultaneously on a second *"fast" camera* (See Fig. 4-161 for explanation.)

Note that a fairly complete picture of the hemodynamic status of this patient (a 45-year-old woman) is contained on this single recording, which was obtained over a period of 200 sec. This recording establishes that she *has* (1) completely irregular heart rate (atrial fibrillation), (2) a normal *systemic arterial pressure and blood oxygen saturation*, (3) a normal respiratory rhythm and rate, (4) blood pressures *in the* pulmonary artery, right ventricle, and right atrium that are in the high range of normal value, *(5) a* severe degree of arterialization of blood at the right atrial level and an extremely high pulmonary blood flow, *presumably* due to an atrial septal *defect, and (6) a* systemic cardiac output that is probably *below the* range of normal values, since the *systemic* oxygen saturation of venous blood *withdrawn from the superior* vena cava is *below the* range of normal values for a person breathing 99.5 *per cent* oxygen. The approximately 20 ml of *blood* withdrawn through the cuvette oximeter for the oxygen-saturation analyses is *kept* sterile and immediately returned *through the* cardiac catheter after the period of 3 to *4 min* during which these *recordings are made* Note *the striking* increase in light transmission of the *blood* that occurs during the periods when *blood* remained *stationary in the* cuvette These *periods* of absent blood flow in the cuvette are delineated by *dashed* double-headed *arrows* and vertical lines.

arteries to permit calculation of pulmonary blood *flow by* the Fick method (Figs 4-165 and 166)

After the blood *samples have been obtained,* preparations are made to *record* an indicator-dilution curve after *injection* of dye into the main pulmonary artery If a curve of normal contour is *obtained* after this injection, it is confirmatory evidence that a left-to-right shunt of significant magnitude *is* not present However, a *series of blood* samples is analyzed for oxygen saturation as *these samples* are with-

drawn through the cuvette oximeter in a rapid sequence from the pulmonary artery, the outflow portion of the right ventricle, the inflow portion of the right ventricle, the right atrium, and the superior vena cava (Fig. 4-167). Continuous pressure recordings also are obtained as the catheter tip is moved between each pair of these sites (Fig. 4-168). This series of analyses and pressure recordings can be completed in less than 5 min (Fig. 4-167), thus minimizing the probability of any change in the physiological status of the patient interfering with the interpretation of the results. If blood samples of significantly different oxygen-saturation levels are obtained at any of these locations, such as between the pulmonary artery and the outflow tract of the right ventricle, or between the outflow tract and the lower part of the right ventricle, then this problem is reinvestigated in the same way as previously described for a situation involving the right atrium Thus, if the suspicion is raised that there is minimal arterialization in the pulmonary artery, then blood samples are taken successively across the pulmonary valve and as many as six samples, three in the pulmonary artery and three in the outflow portion of the right ventricle, are taken to rule out the presence of this arterialization in the pulmonary artery In the same way, it is convenient to take samples across the tricuspid valve to establish or exclude the presence of arterialization in the right ventricle. Care must be taken in this regard not to be misled by a low oxygen saturation level in a sample from the lower part of the right atrium; this may be caused by contamination with blood from the coronary sinus.

The sensitivity of detection of left-to-right shunts by the conventional method of withdrawing blood samples from various sites within the heart and great vessels and subsequent manometric analysis of the oxygen content of these samples has been criticized. This sensitivity can be considerably improved by means of repeated series of successive photometric analyses for oxygen saturation of flowing blood being withdrawn via the cardiac catheter from selected sites upstream and downstream to the region of a suspected left-to-right shunt. Such a series of two to four rapidly consecutive analyses can be completed in 2 to 4 min and this procedure can be repeated until the results obtained seem to establish the presence or absence of a left-to-right shunt with certainty. By means of this technique, it is possible, under usual circumstances, to detect left-to-right shunts comprising 10 to 15 per cent of the total pulmonary blood flow.

Experience in the authors' laboratory supports the impression that the sensitivity of detection of left-to-right shunts by properly applied analyses of blood oxygen saturation by means of cuvette oximetry is adequate for most practical diagnostic purposes. This statement is supported by the fact that, to the

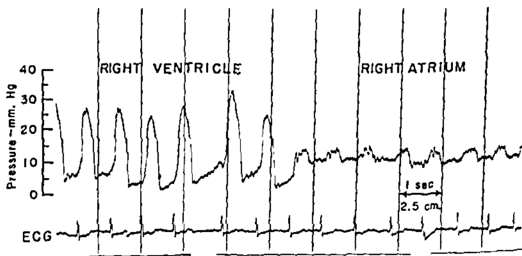


Fig. 4-168. Segment of a photokymographic recording obtained on the "fast" camera during withdrawal of the catheter tip from the right ventricle to the right atrium. Note that during diastole the pressure in the right atrium is considerably greater than the diastolic pressure in the right ventricle, thus establishing the presence of significant tricuspid stenosis The breaks in the base line are signals indicating the beginning and end of the period of withdrawal of the catheter.

authors' knowledge, in the absence of combined septal defects or aortopulmonary communications, a falsely negative or positive diagnosis of a left-to-right shunt has never been made following cardiac catheterization in their laboratory. This experience includes approximately 500 patients in whom the diagnosis at catheterization could be checked by the surgical findings during operative correction of the atrial or ventricular septal defects or aortopulmonary communications.

More sensitive methods for detection of left-to-right shunts are available. All of these techniques are, however, considerably more cumbersome than cuvette oximetry. The *nitrous oxide method* has been advocated by Sanders and coworkers, as has the use of *radioactive gases* Apparently the most sensitive method for the detection, localization, and quantitation of a left-to-right shunt is the *indicator-dilution method* described by Fox and Wood This procedure involves recording of dilution curves of cardio green dye in blood samples taken from the right side of the heart, at sites upstream and downstream from the region of the suspected left-to-right shunt, after injections of the dye via a second catheter lumen or a second catheter at a site downstream from the defect, usually a distal pulmonary artery This method is of particular value in the technically difficult problem of detecting a second (downstream) left-to-right shunt in patients with multiple defects.

An indicator-dilution curve is then recorded after injection into the superior or, preferably, the inferior vena cava, if this curve is normal in contour, the procedure is terminated. The needles in the radial artery and the catheter are removed, and gentle pressure is maintained over the sites of puncture for 3 to 5 min If all pressure and blood oxygen saturation values fall within the range of normal and if abnormal differences in these values at different levels in the heart have not been detected, the diagnosis of an apparently normal central cardiovascular system is entertained

ABNORMAL FINDINGS DURING CARDIAC CATHETERIZATION: THEIR ELUCIDATION

An outline and elucidation of the findings that may be encountered in the presence of significant heart disease follow. Ordinarily, cardiac catheterization in the presence of heart disease is performed in an orderly sequence, as already described. However, deviations from this routine will be mentioned, wherever they are deemed necessary to obtain the best possible clarification of the different conditions under discussion. Four types of information may be obtained during right heart catheterization, namely, (1) the normality or abnormality of the position taken by the catheter when its tip lies in known or identifiable positions, (2) abnormal pressure levels or contours, (3) abnormal values for blood oxygen saturation, and (4) normal or abnormal contours of indicator-dilution curves recorded at selected sites in the arterial or venous circulations, or both, after injections at selected sites in the vascular system.

Abnormalities at Level of Right Atrium or Great Veins. Increased venous pressure may be caused by abnormalities in right atrial pressure or may be due to venous obstruction. Localized obstruction may result from conditions involving the great veins prior to their entry to the heart, e.g., carcinoma of the lungs, which may infiltrate and obstruct the great vessels. Conditions causing generalized increase of right heart pressure include congestive heart failure and constrictive pericarditis. An A wave of large amplitude in the tracing of right-atrial pressure suggests active atrial contraction. If the principal wave in the atrial tracing is a *V wave*, this suggests the presence of valvular regurgitation (Gorlin et al).[11]

Blood Oxygen Saturation Values. If the oxygen saturation of systemic venous blood, as judged by the saturation of blood samples drawn from the inferior and superior venae cavae is below the 95 per cent confidence range of normal values, which means values of 73 and 67 per cent, respectively, while the arterial oxygen saturation is within the normal range, then it is likely that the cardiac output is reduced, as in acquired heart disease and congenital disease associated with heart failure. *In unanesthetized persons*, since the oxygen saturation of inferior caval blood exceeds the saturation of superior caval blood, a blood oxygen saturation of superior caval blood in excess of that of inferior caval blood suggests the following possibilities: (1) an anomalous pulmonary venous connection to the superior vena cava, (2) a systemic arteriovenous fistula

[11] For terminology and interpretation of this wave, see below, Patterns of Pressure Editor.

in the upper portion of the body, or (3) the presence of a patent ductus arteriosus with severe pulmonary hypertension and a consequent right-to-left shunt, which is primarily to the lower portion of the body. The usual conditions resulting in an abnormally increased blood oxygen saturation in the right atrium or in the veins immediately adjacent to this chamber include (1) atrial septal defect; (2) common atrioventricular canal; (3) anomalous pulmonary venous connections; (4) tricuspid regurgitation associated with ventricular septal defect; (5) ventricular septal defect with entry directly into the right atrium; (6) total anomalous pulmonary venous drainage; (7) systemic arteriovenous fistula; and (8) ruptured aneurysm of the sinus of Valsalva into the right atrium.

The first problem in the elucidation of these conditions is the establishment of the presence of arterialization at the right atrial level. When the degree of arterialization is small, it may be necessary to withdraw four or five series of blood samples successively from the inferior vena cava, right atrium, and superior vena cava in order to demonstrate this abnormality with certainty. Maximal arterialization high in the right atrium or superior vena cava rather than in the middle and lower portions of this chamber is strongly suggestive of the presence of an anomalous connection of the pulmonary vein to the superior vena cava (Swan et al.) or of anomalous pulmonary venous drainage via a persistent left vertical vein connected to the left innominate vein. Further elucidation of the location and site of the left-to-right shunt depends on other data (Swan et al.).

Positions Other than Right Ventricle or Inferior Vena Cava Entered from Right Atrium. It is not uncommon for the cardiac catheter to enter *the coronary sinus*, an occurrence that usually can be recognized by the typical position of the catheter The finding that the oxygen saturation of blood drawn from this location is significantly (and usually strikingly) lower than that of blood from the right atrium confirms the nature of this vessel A persistent left superior vena cava, when present, usually joins the coronary sinus and drains by this vessel to the right atrium. The incidence of entry of the catheter into the coronary sinus is more frequent in the presence of a persistent left superior vena cava.

When an *interatrial communication* exists, the catheter frequently enters *the left atrium*, this may be confirmed by the demonstration of the high oxygen saturation of blood drawn from this location, usually not significantly lower than that of systemic arterial blood. If the catheter is advanced so that its tip enters *the left ventricle* or *a pulmonary vein*, the sequence of the procedure may be interrupted to place a needle in a systemic artery for simultaneous recording of pressures and the oxygen saturation of blood withdrawn from a systemic artery and from the left side of the heart, and for recording indicator-dilution curves after injections of indicator into the left side of the heart.

When the catheter tip lies *in the left ventricle*, the simultaneous recording of systemic and left ventricular pressure serves to suggest or exclude the presence of aortic stenosis, certain malformations of the great vessels or abnormalities of left ventricular function. The position of the catheter should be confirmed roentgenographically, since the differences in position in atrial septal defect (fossa-ovalis type) and in persistent common atrioventricular canal have diagnostic significance (Wakai et al.). A dilution curve recorded after injection into the left ventricle will serve to confirm or exclude the presence of a left-to-right shunt at or distal to the left ventricle, or of severe regurgitation of the mitral or aortic valves. The oxygen saturations of systemic arterial and of left ventricular blood are compared, since the possibility of *a right-to-left aortopulmonary shunt* must be considered if they differ significantly. With a continuous record of pressure to elucidate the status of the mitral valve, the catheter is withdrawn to the left atrium. A second injection of dye is made in this chamber to ascertain the presence of *left-to-right shunting* at or distal to the level of the left atrium.

If the catheter has entered *a pulmonary vein*, the oxygen saturations of pulmonary venous and of systemic arterial blood are compared to aid in the detection of any degree of right-to-left shunting. Further, it is important to recognize the presence of pulmonary venous desaturation, which may be caused by underventilation associated with anesthesia, since significant alterations in pulmonary dynamics are associated with hypoxia. The pressure in the pulmonary vein is recorded and the catheter is advanced to the "venous wedge" position,

since this pressure *may give useful* evidence as to the presence or absence of pulmonary *hypertension* (Connolly and Wood). With the catheter free in a pulmonary vein, its position is confirmed roentgenographically, and an indicator is injected Comparison of the resulting *arterial* dilution curve with that obtained after injection into the superior and inferior venae cavae permits designation of the drainage from the pulmonary vein in terms of the systemic *drainage* to the right atrium. Closely *similar* dilution curves indicating similar drainage suggest that the vein is abnormally connected, while *dissimilar* curves indicate different drainage patterns and imply that the vein is connected to the left atrium Recourse to these techniques is necessary since it may be difficult or impossible to determine the site of connection of a right pulmonary vein from the roentgenographic appearance of the catheter when its tip passes into a right pulmonary vein from the silhouette of the right atrium This difficulty does not apply to anomalous connections to the superior vena cava or, usually, to positions of the catheter in the veins of the left lung

A record of pressures should be obtained during withdrawal of the catheter tip from the *left ventricle or from* the pulmonary vein to the right atrium, since a decrease in mean pressure of 3 mm Hg between the left atrium and the right atrium implies that the interatrial communication is either smaller than usual or that it is guarded by a competent valve

Abnormal Findings at Level of Right Ventricle. If the right ventricular systolic pressure exceeds 40 mm Hg, then some degree of right-ventricular hypertension is present The configuration known as *the square root sign*, associated with conditions (such as constrictive pericarditis) that interfere with diastolic relaxation of the left ventricle should be sought in the diastolic portion of the recording of the right ventricular pressure pulse (Connolly and Wood; Burwell) *The demonstration*, on withdrawal of the catheter *from the right ventricle* to the right atrium, of a diastolic AV pressure gradient of 2 to 4 mm suggests the presence of tricuspid stenosis (Fig 4-168) An apparently abnormal position of the tricuspid valve may suggest the diagnosis of Ebstein's malformation of this valve.

In the absence of arterialization in the right atrium, arterialization in the right *ventricle* can be said to be demonstrated if right ventricular saturation is found to consistently exceed the saturation of right atrial blood *by more than 2 per cent* in repeated pairs of blood samples withdrawn in rapid succession from the lower part of the right ventricle and the right atrium just outside the tricuspid valve. The common causes of arterialization in the right ventricle are ventricular septal defects, the complete type of *atrioventricularis communis* with a left-to-right shunt at the ventricular level, patent ductus arteriosus with pulmonary regurgitation, a ruptured aneurysm of the sinus of Valsalva opening into the right ventricle, and the rare condition of an aberrant opening of a coronary artery into the right ventricle.

If an atrial septal defect is present and arterialization has been demonstrated at the right atrial level, the possibility of demonstrating an additional left-to-right shunt through a ventricular septal defect or common atrioventricular canal is considerably less than when arterialization at the atrial level is absent During withdrawal of the catheter from the lower part of the right ventricle to the right atrium, if its tip remains in a position just outside the tricuspid valve during withdrawal of the right atrial sample, and if this can be accomplished several times in succession, then the presence of additional arterialization at the right ventricular level can be strongly suspected if the oxygen saturation of the right-ventricular blood consistently exceeds that of the right atrial blood by more than 2 to 4 per cent. However, if the catheter tip passes to the lower or midlateral portion of the right atrium when it is withdrawn from the right ventricle to just outside the tricuspid valve, the significance of a higher saturation of blood withdrawn from the right ventricle *must be greatly* discounted due to preferential flow of the arterialized (left-to-right shunted) blood through the tricuspid valve without uniform mixing in the right atrium.

Abnormal Findings at the Level of the Pulmonary Valve. If the pulmonary-arterial systolic pressure exceeds 30 to 35 mm Hg in a resting person, some degree of pulmonary hypertension can be presumed to exist A continuous pressure recording should be obtained during slow withdrawal of the catheter tip across the region of the pulmonary valve. A *small* pressure gradient ranging up to 7 mm

is found in normal persons. In the absence of increased pulmonary blood flow, a systolic pressure gradient across the pulmonary valve greater than 10 mm, if consistently present, can be taken as evidence of some degree of pulmonary valvular stenosis. In patients who have large left-to-right shunts with later confirmed absence of anatomic pulmonary stenosis, pressure gradients of 20 mm across the pulmonary valve are not infrequent and gradients as high as 40 mm [12] have been found (Weidman et al.).

If a significant decrease in systolic pressure occurs during advancement of the catheter tip across the region of the pulmonary valve, several continuous pressure recordings should be obtained during slow withdrawal of the tip across this region to obtain supporting evidence as to whether the stenosis is *valvular*, or *infundibular*, or *both*. When pronounced valvular stenosis is present, a severe underlying infundibular stenosis may not be demonstrable by pressure recordings until surgical relief of the valvular stenosis has been accomplished. However, *a sharp change in systolic pressure* that can be localized with a reasonable degree of certainty at or near the pulmonary valve is strong evidence of valvular stenosis. *If a clear-cut zone of intermediate pressure* can be demonstrated between the pulmonary valve and the lower part of the outflow tract of the right ventricle, either alone or in conjunction with a systolic pressure gradient at the region of the pulmonary valve, this can be accepted as proof of *infundibular pulmonary stenosis.*

Unless the lesion is extremely severe, a clear demonstration of *pulmonary valvular regurgitation* usually cannot be obtained on the basis of recordings of pulmonary-arterial and right ventricular pressures.

It is not uncommon to be able to demonstrate significant arterialization of blood withdrawn from the outflow tract of the right ventricle in the absence of arterialization in the inflow portion of this chamber. This may occur in patients who have (1) small ventricular septal defects located in the region of the membranous septum; (2) an aortopulmonary communication with pulmonary regurgitation; or (3) a ruptured aneurysm of the aortic sinus. The most prominent degrees of this phenomenon have been encountered in patients with infundibular pulmonary stenosis with a ventricular septal defect opening on the low-pressure (downstream) side of the stenosis.

In patients with a ventricular septal defect in the usual location and a large left-to-right shunt, it is common to find a more severe degree of arterialization in the outflow portion of the right ventricle. This is presumptive evidence that the ventricular septal defect lies in the region of the membranous septum. If no evidence of additional arterialization is found in the outflow portion of the right ventricle, and particularly if one or more blood samples of greater oxygen content are obtained from the lower part of the right ventricle, this constitutes evidence suggestive of a "low" defect in the muscular portion of the ventricular septum.

Abnormal Findings at the Level of the Pulmonary Artery. If the systolic pressure in the pulmonary artery exceeds 35 mm Hg while the patient is at rest, a cause for this abnormality should be sought. *Pulmonary hypertension* may be associated with increased pulmonary blood flow; if a defect in the heart or great vessels that might permit a left-to-right shunt has already been demonstrated, it is likely that this change is a consequence of the congenital defect. Great increase in pulmonary arterial pressure is not a common accompaniment of atrial septal defect. When the size of a ventricular septal defect or patent ductus arteriosus exceeds 1 cm^2/m^2 of body surface, pressures approaching, or equal in magnitude to, systemic pressure are present in the pulmonary artery in the absence of pulmonary stenosis.

If a congenital defect has not been demonstrated and the level of pulmonary arterial pressure is equivalent to that of aortic pressure, great care must be taken to exclude the possibility of an interventricular or aortopulmonary communication that is masked because of the presence of closely equivalent pressures on the right and left sides of the heart, so that a left-to-right shunt is absent or minimal and a right-to-left shunt, if present, is too small to be easily detected by demonstration of a decrease in oxygen saturation of arterial blood.

[12] The existence of such a large gradient of pressure without organic stenosis is not universally accepted and should be considered at least as an exceptional possibility. *Editor.*

Tests that may produce differential effects on the pulmonary and systemic circulation, such as exercise or the breathing of high or low concentrations of oxygen, may be used in the presence of severe pulmonary hypertension in an attempt to unmask defects previously hidden by the closely balanced pressures that may exist at the level of the defect on the right and left sides of the circulation

Since extremely small right-to-left shunts (less than 5 per cent of systemic flow) can be detected by the indicator-dilution method, such defects usually can be demonstrated after injection of indicator at appropriate sites in the pulmonary artery, right ventricle, and right atrium (Swan et al) However, if the defect is a patent ductus arteriosus, the dilution curve must be recorded from the descending aorta or its tributaries (a femoral artery) in order to exclude the possibility of a small right-to-left shunt into the descending thoracic aorta from this source Differences in the oxygen saturation of blood withdrawn from the right radial and femoral arteries are due to the preferential flow of "venous" blood from the pulmonary artery into the descending aorta via the patent ductus (Burchell et al)

In the absence of arterialization at the ventricular level, an aortopulmonary left-to-right shunt is demonstrated if the oxygen saturation of the pulmonary blood uniformly exceeds that of right ventricular blood by more than two percentage points when successive pairs of these samples are withdrawn in rapid succession from above and just below the pulmonary valve The most common cause for this finding is a patent ductus arteriosus, less commonly, one finds an aortopulmonary septal defect, and, rarely, a coronary artery that opens into the pulmonary artery is seen

When arterialization has been noted in the right ventricle, the problem of demonstrating an additional left-to-right shunt at the level of the pulmonary artery is much more difficult, since the sensitivity of the detection of a left-to-right shunt by demonstration of an abnormal increase in blood oxygen saturation at a given site in the right heart circulation is inversely related to the difference in oxygen saturation of the systemic arterial blood and the "venous" blood flowing into the chamber or vessel in question. Therefore, if severe arterialization is present in the right atrium or ventricle, a large left-to-right shunt occurring concomitantly at the level of the pulmonary artery may escape detection and the presence of a patent ductus arteriosus may be unsuspected unless the catheter passes through it (Bowers et al). Furthermore, if the left-to-right shunt at the ventricular level is just below the pulmonary valve, it is possible for blood traversing the defect to enter the pulmonary artery without mixing uniformly with the blood in the outflow portion of the right ventricle When the catheter tip is withdrawn to a position just below the pulmonary valve, it is possible to sample preferentially blood of a more venous character coming from the lower part of the right ventricle and thus to gain the impression that additional arterialization is occurring at the level of the pulmonary artery. Under this circumstance, during the process of withdrawal of successive pairs of samples from the pulmonary artery and right ventricle, the position of the catheter tip when it is withdrawn through the pulmonary valve should be observed closely. If the tip shifts laterally as it moves down through the valve, the significance of a lower oxygen saturation of the right ventricular blood should be suspect. Under these conditions, if even one sample of blood obtained from just below the pulmonary valve has an oxygen saturation equal to or significantly greater than that of any of the samples withdrawn from the pulmonary artery, this should be taken as strong presumptive evidence against a coexisting patent ductus arteriosus.

If the presence of congenital intracardiac and great-vessel septal defects has been excluded, the next possible cause of pulmonary hypertension to be elucidated is obstruction to pulmonary venous drainage, such as may be produced by (1) mitral valvular disease, (2) left ventricular failure or restriction of the distensibility characteristics of the left ventricle during diastole, (3) tumors encroaching on the left atrium or pulmonary veins, or stenosis of the pulmonary veins; and (4) cor triatriatum and variations thereof *A condition producing obstruction to pulmonary venous drainage can be considered to exist if the pulmonary-artery wedge pressure is significantly above the normal range* If this wedge pressure is normal and if results of all the afore-mentioned attempts to demonstrate a congenital

defect are normal, the diagnosis can be presumed to be *idiopathic pulmonary hypertension* (Shepherd et al.).

An increase of the mean pulmonary-artery wedge pressure above the range of values (8 to 16 mm Hg) obtained in normal resting persons is indicative of either an *increase in left atrial pressure* or *stenosis of the pulmonary veins*. Various conditions producing obstruction to pulmonary venous drainage already have been mentioned, as have the criteria for establishing the validity of the wedge pressure as an indication of pulmonary venous pressure in a given patient If the pulmonary-artery wedge pressure is increased, particular attention should be paid to the contour of the pressure tracing and the relation of the peak V-wave pressure to the mean wedge pressure. The presence or absence of a disproportionate increase in peak V-wave pressure and other features of its contour are important in the differentiation of mitral regurgitation from mitral stenosis and other conditions causing an obstruction to pulmonary venous drainage (Connolly and Wood, 1957, Marshall et al, 1958).

If the increase in pulmonary-artery wedge pressure is questionable or only slight, it may be of value to have the patient exercise in order to determine whether an abnormal increase in this pressure occurs during this form of circulatory stress Accurate assessment of the significance of increased wedge pressure during rest or exercise requires knowledge of the rate of pulmonary blood flow when this pressure is measured

Simultaneous measurements of intravascular and intracardiac pressures and blood flows during exercise can be obtained most expeditiously if the exercise is confined largely to the legs and accessory muscles and is carried out in the supine position. The muscular activity involved in pedaling a bicycle type of ergometer designed for use in the supine position and for easy attachment to the fluoroscopic table is a convenient form of exercise and is suitable for most diagnostic purposes (Fig 4-165).

Abnormal Pathways of Catheter from Right Ventricle or Pulmonary Artery. The aorta may be entered from the right ventricle via a ventricular septal defect In such cases, the catheter may enter the right ventricle with ease but then it passes into a central vessel that lies in the center or to the right of the cardiac silhouette. An aortic type of pressure and blood equal in oxygen saturation to that of a systemic artery are demonstrated. Under such circumstances, attempts should be made to advance the catheter so that its tip traverses the arch of the aorta, allowing the position of this vessel to be identified. The peripheral and central (aortic) systemic arterial pressure and blood oxygen saturation should be recorded simultaneously, and a selective dye-curve sequence should be carried out, with injections of dye into the aorta just above the semilunar valve, into the lower part of the right ventricle, and into the superior vena cava. This series of dye-dilution curves will provide evidence concerning (1) the presence or absence of a left-to-right shunt originating from the aorta, or of aortic insufficiency; (2) the presence or absence of a right-to-left shunt at the ventricular or atrial level; and (3) the presence or absence of two routes of egress of blood from the right ventricle (Weil and Swan).

When the catheter enters the pulmonary artery from the right ventricle, its position at the moment of transition from a pulmonary arterial to a ventricular type of pressure, and when in the pulmonary artery, should be noted. If the pulmonary artery appears to be farther toward the right than usual, roentgenograms in both anteroposterior and lateral views should be taken in order to obtain evidence for or against the possible presence of *transposition of the great vessels* (Fig. 4-169). The possibility of this malformation should be considered when unusual difficulty is encountered *in manipulating the catheter* into the pulmonary artery.

A catheter may pass from the pulmonary artery into the aorta via *a patent ductus arteriosus* or *an aortopulmonary window.* The differentiation frequently can be achieved by use of anteroposterior and lateral roentgenograms If the catheter enters the cephalic arteries, particularly the innominate, it is extremely improbable that the catheter has traversed a patent ductus arteriosus in the usual location. The demonstration of preferential shunting of venous blood to the descending aorta or of an indicator injected at, or proximal to, the level of the pulmonary valve is evidence for a patent ductus arteriosus. It may be diffi-

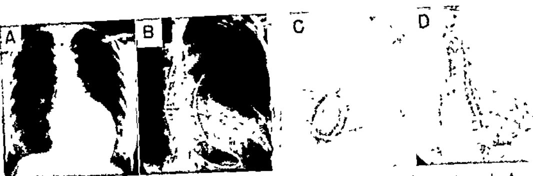


Fig. 4-169. Roentgenograms of a patient with corrected transposition of the great vessels. A. Routine posteroanterior roentgenogram of thorax. B A cardiac catheter has been passed through the right ventricle and its tip is wedged in a small pulmonary artery in the left upper lobe. C. Lateral view with the catheter in the same position as shown in (B). D The catheter has been withdrawn so that its tip lies in the left pulmonary artery. Note on posteroanterior views that the catheter, when traversing the pulmonary valve, is displaced to the right in relation to the usual situation and displaced dorsally in the lateral view. (H. F. Helmholz, Jr. et al. Proc. Staff Meet Mayo Clin 1956)

cult on occasions to distinguish when a catheter enters the aorta via a ventricular septal defect and when it enters via an aortopulmonary window This differentiation is possible on demonstration that the blood obtained just above the pulmonary valve is of lower oxygen saturation than blood from the aorta.

COMPLETION OF PROCEDURE

The remaining steps in cardiac catheterization at this stage depend upon the data obtained in the preceding portion of the procedure If the pulmonary-artery wedge pressure is increased, it may be of value to study the effect of exercise on the wedge and pulmonary-arterial pressures and on pulmonary blood flow. In mild pulmonary stenosis, the effect of exercise on the gradient of pressure between the right ventricle and the pulmonary artery is of value. If severe pulmonary hypertension is present, the effect of breathing 100 per cent oxygen on pulmonary and systemic pressures and blood flows may be of value in order to ascertain the lability of the pulmonary vascular resistance in relation to the selection of patients for surgical treatment A sequence of indicator-dilution curves after injection of indicator at selected levels in the heart is an indispensible portion of the procedure at this stage of the study As a minimum, dilution curves after injection into the pulmonary artery and superior vena cava are obtained, these curves demonstrate a right-to-left shunt if one is present. The sensitivity of detection of right-to-left shunts by this method exceeds that obtainable by any other technique of which the authors are aware. Localization of the right-to-left shunt is achieved by selective injection at sites proximal and distal to the chamber from which the shunt is occurring. Thus, injections into the pulmonary artery, right ventricle, and superior vena cava permit accurate localization of defects through which a right-to-left shunt is occurring. Furthermore, these dilution curves provide confirmatory evidence of the presence and magnitude of left-to-right shunts and of valvular regurgitation (Korner and Shillingford) In certain specific anomalies, dilution curves of greater diagnostic significance may be obtained (Chap. 6). These are discussed in more detail in another chapter. They include (1) atrial septal defects in which injections of indicator into the right and left pulmonary arteries usually permit the demonstration of preferential drainage of blood from the right lung and of small right-to-left shunts of inferior caval as opposed to superior caval blood, and (2) anomalous connection of the pulmonary veins in which the similarity of drainage of the blood from a particular pulmonary artery or pulmonary vein to the drainage of blood from the right atrium or its tributaries permits correct diagnosis

PROCEDURES WHEN CATHETER WILL NOT ENTER PULMONARY ARTERY AND PULMONARY ARTERY WEDGE POSITIONS

In certain of the more complex anomalies, the catheter cannot be advanced into the pul-

monary artery. It is unusual (in the hands of a skilled and experienced physician) for the catheter not to enter the pulmonary artery unless some anatomical condition predisposes to this result. Conditions to be considered under such circumstances are pulmonary atresia, tricuspid atresia, transposition of the great vessels, Ebstein's malformation, or severe enlargement of the chambers of the right heart. In these and other conditions, use of *indicator-dilution curves* may make the correct diagnosis possible The use of *selective angiocardiography* in certain cases may permit a diagnosis that is not possible by other methods.

In the presence of severe pulmonary hypertension, it may not be possible to advance the catheter from the pulmonary artery to the pulmonary artery wedge position Inability to attain a wedge pressure is usually not of great consequence in right heart catheterization unless the presence of a lesion in the left side of the heart or pulmonary veins is suspected, or pulmonary hypertension is present without an apparent cause If knowledge of the left atrial pressure is sufficiently necessary to justify the procedure, recourse can be had to left heart catheterization, either during or subsequent to study of the right side.

The incidence of difficulty in manipulating the catheter tip into the desired positions (as the result of causes not directly related to cardiovascular disease) is greatest in small infants, because of technical difficulties in introducing and manipulating catheters in small veins and the high incidence of venospasm when the internal diameter of the vein used is not appreciably larger than the external diameter of the catheter introduced into this vein. The incidence of inability to manipulate the catheter into the desired position when pathological changes are present in the heart and great vessels is also highest in procedures carried out in infants and small children because of the greater incidence of complex defects in this group

If the catheter has not been manipulated into the pulmonary artery despite reasonable persistence, the physician should make sure that sufficient series of blood samples and of pressure recordings have been obtained from the right ventricle, right atrium, and great veins to establish the absence or nature of abnormalities at those levels in the heart that have been entered by the catheter. Then a suitable sequence of indicator-dilution curves should be recorded and, if necessary, one or more selective angiocardiograms should be made to obtain the maximal clarification as to the most probable anatomic and hemodynamic changes present.

When the catheter tip cannot be introduced into the pulmonary artery, it sometimes can be passed into another central arterial vessel (aorta or truncus arteriosus). Entrance of the catheter tip into such a central arterial vessel is of considerable assistance in establishing a firm diagnosis, since the position of the catheter and a comparison of the pressure and oxygen saturation of the blood in this vessel with that existing simultaneously in a systemic artery and the recording of dilution curves after injection of indicator into this vessel establish the relationship of this vessel to the systemic and pulmonary arterial circulation. This information allows demonstration of the presence or absence of right-to-left or left-to-right shunts at the level of the great vessels and of the presence of two paths or only one route of egress of blood from the heart.

INABILITY TO ENTER RIGHT VENTRICLE

If the right ventricle cannot be entered, indicator-dilution curves should be recorded at a systemic artery after injection into the sites entered by the catheter tip, such as the superior and inferior venae cavae and also the left atrium, left ventricle, and pulmonary veins, if any of these latter sites should have been entered by the catheter. Such dilution curves will usually demonstrate whether a functioning right-ventricular–pulmonary-arterial pathway is present and, therefore, establish or exclude the diagnosis of tricuspid atresia (Birkhead and Wood).

TECHNICAL DIFFICULTIES IN THE USE OF CARDIAC CATHETERIZATION

Venous spasm is encountered in 5 to 10 per cent of patients undergoing cardiac catheterization. Its incidence is related to the diameter of the catheter and the size of the vein through which catheterization is performed. For this reason, cardiac catheters of the smallest possible external diameters are preferred. The selection of a medial antecubital vein in preference to a lateral vein considerably reduces the incidence of venous spasm When severe venous spasm interferes with manipulation of the catheter, insertion of a wire stylet may allow continuation of the procedure (Fig 4-162B). On continued gentle movement of the catheter, it is not uncommon for a certain degree of relaxation of the spasm to occur and manipulation then may proceed with greater ease.

Inability to manipulate the catheter into the heart occasionally occurs during cardiac catheterization, particularly in infants. Recourse may be had to a vein in the leg, from which catheterization almost always can be achieved without great difficulty However, use of this site for manipulation frequently interferes significantly with entry into the pulmonary artery.

COMPLICATIONS

Minor or severe complications during cardiac catheterization occur most frequently in procedures carried out on infants or small children, who are under general anesthesia or balanced amnesia and analgesia Because of the criteria for selection of patients in this age group for catheterization, a great incidence of severe heart disease is present in these patients, so that the inherent risk of anesthesia as well as of the catheterization is increased.

Underventilation with hypoxemia and hypercapnia is relatively common in such patients, either as a result of depression of the respiratory center by the anesthetic agents, or because of varying degrees of respiratory obstruction The existence of hypoxemia can be detected by continuous monitoring of the arterial oxygen saturation by means of the ear oximeter. This condition may constitute a serious danger to the patient, and it al[illegible] interferes with interpretation of the

[illegible]

to errors that may be large and of unknown magnitude This difficulty can be circumvented to a degree by estimation of the shunts on the basis of indicator-dilution curves

Cardiac Arrhythmias. Extrasystoles and other transient disturbances in rhythm or rate are encountered almost *uniformly when* the tip of a cardiac catheter is manipulated into the right ventricle and through it into the pulmonary artery Despite their usual occurrence, such arrhythmias are always a source of worry, since a small but nonetheless definite possibility exists that they may presage the onset of *ventricular fibrillation.* The electrocardiogram should be monitored closely during this manipulation, which should be stopped immediately or altered in character if severe arrhythmias occur

A sustained arrhythmia, such as atrial fibrillation or tachycardia, occasionally may ensue during the procedure If severe underlying heart disease is present, such arrhythmias may endanger the patient and thus *require* immediate treatment In the authors' experience, a rapidly acting cardiac glycoside, such as deslanoside (Cedilanid-D) given intravenously has been the most effective drug in the treatment of *persistent* regular tachycardia under such circumstances.

Emergency equipment for treatment of the severe arrhythmias (ventricular fibrillation or possibly *cardiac arrest*) frequently associated with sudden death should be available on a stand-by basis during cardiac catheterization *This equipment* should include (1) an external and internal defibrillator and cardiac pacemaker, (2) a laryngoscope, endotracheal tubes, oxygen, and equipment for maintaining artificial *respiration,* (3) instruments for performing emergency *thoracotomy;* and (4) suitable stimulant and supportive drugs, including epinephrine and norepinephrine

The team performing cardiac catheterization should have *experience* in the resuscitation of dogs from electrically induced ventricular fibrillation using the same defibrillation apparatus kept on a stand-by basis for clinical catheterization. This experience should include *defibrillation* with a closed *and an open thorax,* and the use of *cardiac massage* Adequate precautions should be taken to protect the personnel participating in such resuscitative procedures, particularly from the high voltage and currents required for successful external *defibrillation* Although the authors have not had occasion to attempt *external defibrillation* on a patient, it is believed on the basis of experience gaine[illegible] from many studies on dogs[14] that this [illegible]nt- techr[illegible] fi- age [illegible] illa- brillation is [illegible] tion is not precipitated by severe cardiac hypoxia due to hypoxemia or hypotension, the underlying cause of which cannot be immediately remedied; or (3) the underlying heart disease is not so *severe* that *recovery from temporary decompensation is unlikely.*

In the 1,710 right heart catheterizations carried out at the Mayo Clinic, ventricular fibrillation has occurred in two patients, the onset of ventricular fibrillation in both was preceded by a period of ventricular tachycardia that produced a *severe decrease in systemic arterial* pressure. Study of the continuous recordings obtained during these periods supports the interpretation that the ventricular fibrillation was secondary to cardiac hypoxia resulting from the great decrease in coronary perfusion pressure associated with *the tachycardia The occurrence of these serious* arrhythmias and the authors' inability to resuscitate these patients from the ensuing ventricular fibrillation are thought to be related to the fact that each patient had multiple and severe congenital cardiac defects

[14] The equipment used was a *combined* cardiac pacemaker and an *internal and external* defibrillator assembly manufactured *by the* Levinthal Products Co, Stanford *Industrial Park,* Palo Alto

Necropsy in one patient, a woman, disclosed a large ventricular septal defect, a large patent ductus arteriosus, and severe mitral insufficiency; necropsy in the other patient, a 3-year-old girl, disclosed an atrial septal defect associated with severe mitral and pulmonary stenosis. During catheterization in this child, which was carried out with the patient under general anesthesia, progressive arterial desaturation occurred. On the basis of subsequent study of the continuous recordings obtained throughout the procedure, this arterial desaturation, which was probably a predisposing factor for the arrhythmia, was considered to have been caused by undetected collapse of the left lung.

Sustained atrial fibrillation has occurred in seven patients during these 1,710 procedures, and sustained severe tachycardia has been noted in 22 patients. Except for the two patients in whom ventricular fibrillation ensued, the tachycardia was replaced by a normal sinus rhythm within an hour in every instance, either spontaneously or after intravenous administration of deslanoside.

There were three patients in whom *temporary cardiac arrest* of more than 20 sec occurred. Normal rhythm returned spontaneously in each of these patients In one instance, the arrest occurred during the performance of a selective angiogram of the right ventricle on a patient who had tetralogy of Fallot with pulmonary atresia, and in whom a large portion of the contrast medium entered the ascending aorta and cerebral vessels. This patient died with evidence of cerebral damage 12 hr after the procedure. The other two patients, in whom selective angiocardiography was not performed, had no apparent sequelae

Morbidity and Mortality of Right Heart Catheterization. Information concerning the morbidity and mortality rates encountered in 5,700 right heart catheterizations carried out in six institutions in the United States has been presented by Cournand and associates Four deaths occurred in this group of patients, an incidence of less than 0.1 per cent.

Review of the experience in the authors' laboratory reveals that four deaths have occurred during 1,710 right heart catheterizations, an incidence of approximately 0.2 per cent One of these deaths resulted from an acute asthmatic attack that occurred before the catheter was introduced into the thorax and presumably, therefore, was not the direct result of cardiac catheterization. Two deaths in which ventricular tachycardia was followed by ventricular fibrillation already have been mentioned. The fourth death was that of a 46-year-old man and it occurred 3 hr after the procedure had been terminated due to the onset of precordial pain and electrocardiographic evidence of myocardial ischemia. Necropsy was not performed in this case. The diagnosis on the basis of data obtained during catheterization was ventricular septal defect, probably of the persistent atrioventricular canal type, and severe pulmonary hypertension, with the shunt being predominantly from right to left. The catheter tip had entered and been withdrawn from the aorta shortly before the onset of the precordial pain. This death is presumed to have been caused by coronary occlusion, possibly on the basis of an embolism resulting from the right heart catheterization

A total of 13 patients have died within the period from 6 to 26 hr after completion of right heart catheterization. Two of these patients were adults, one was a 16-year-old boy, and the remainder were small children or infants in whom the procedure was carried out with the aid of general anesthesia. A summary of the clinical and diagnostic information in these 17 patients is given in Table 4-37.

Nonfatal Complications during and Subsequent to Right Heart Catheterization. The occurrence of venospasm and cardiac arrhythmias or conduction defects has already been discussed

SYNCOPAL SYNDROME. This syndrome is characterized by pallor, perspiration, yawning, and frequently nausea. Bradycardia and hypotension usually are present. This reaction rarely occurs during catheterization unless the patient is in a head-up position and then it is usually precipitated by arterial puncture or manipulation of the catheter when some degree of venospasm is present. Transient syncopal reactions when the patient assumes the erect position after termination of the procedure are not rare; consequently, it is important to watch each patient closely after the procedure is completed.

TRAUMA TO ENDOCARDIUM. Traumatic endocardial lesions are frequent as a result of right heart catheterization in animals, but they appear to be relatively uncommon in man. In 79 cases in which necropsy [14] was performed within a period of 0 to 30 days after right heart catheterization, only five instances of relatively minor trauma to the endothelium or endocardium were noted

EMBOLIC PHENOMENA. Complications due to emboli originating from or dislodged by the cardiac catheter would be expected to result from cardiac catheterization A right-to-left shunt was present in every instance in which systemic arterial embolism was suspected to have occurred in this series of cases Three patients exhibited evidence consistent with embolism of a cerebral vessel. Two of these patients had transient hemiplegia that

[14] These studies were made by J. E. Edwards, to whom the authors are indebted for this information.

TABLE 4-37 FINDINGS IN PATIENTS WHO DIED DURING OR WITHIN 26 HOURS AFTER RIGHT HEART CATHETERIZATION *

(1 710 catheterizations 1946 to 1957)

Case no	Sex and age yr	Date of procedure	N Y heart classification	Anesthesia	Diagnosis †			Interval from procedure to death hr	Endocardial trauma	Cause of death and remarks
					Clinical	Laboratory	Pathological			
1	F, 26	11-30-48	IV L	0	RHD MS	Pulm hypt CHF	Granuloma obstructing pulm veins	8	0	Pulmonary edema
2	M 40	3-28-50	II C	0	Hypt *, CHD asthma emphysema	None	Asthma emphysema	0	0	Status asthmaticus catheter did not enter thorax
3	F 25	5-25-51	IV D	0	RHD, MS	MS, MI		26		Pulmonary edema
4	M 16	11-3-52	III D	0	RHD, MS	MS	MS, AI, myocarditis	20	Fibrinous deposits main pulm artery	Pulmonary edema
5	F, 34	1-5-53	IV D	0	VSD with pulm hypt	VSD pulm hypt, MI?, R-L shunt	VSD PDA, MI pulm vascular lesions and hypt	0	0	Tachycardia, anoxemia vent fibrillation, cardiac massage and defibrillation could not restore effective circulation
6	M 46	3-26-54	III D	0	CHD	VSD pulm hypt R-L shunt		3		Thoracic pain, ECG changes shock, death, coronary embolus assumed
7	F 4	10-31-55	III C	+	PS, CHF	PS, CHF	PS, chronic CHF	10	0	Progressive congestive failure, right ventricular pressure very high, and flow low
8	F, 4	2-6-56	II C	+	Trans of great vessels?	VSD, PS	Common vent, inf PS, tricuspid insuff	6	0	Did not regain consciousness, cerebral hypoxia?, selective angiography done
9	F, 11	4 20-56	III C	+	Tetralogy of Fallot?	Single atrium VSD prob truncus arteriosus	Cor biloculare, PS, asplenia	12	0	Gradual circulatory failure, AV dissociation, selective angiography done, three lobes left lung, LSVC, no coronary sinus
10	M 3½	5-29-56	III C	+	PAVC, pulm hypt	PAVC pulm hypt	Partial form of PAVC	18	0	Cerebral edema, pulmonary congestion and edema, did not regain consciousness
11	F, 1 3/12	7-20-56	IV E	+	VSD, pulm hypt	ASD, VSD pulm hypt	ASD VSD, LSVC	17	Small hemorrhage, wall right atrium	Progressive pulmonary edema
12	M ½	8-27-56	IV E	+	ASD, pulm hypt	ASD pulm hypt, cor triatriatum?	Cor triatriatum, ASD	6	0	Progressive pulmonary edema, accessory pulm venous chamber with stenotic communication to right atrium
13	M, 2½	3-13-57	III C	+	VSD, PDA?	VSD	VSD AI	19	0	Pulmonary edema and cerebral hypoxia
14	F, 1 9/12	4-15-57	III C	+	VSD pulm hypt	ASD, prob VSD	VSD LSVC entering left atrium, coronary sinus	22	0	Gradual downhill course, probably cerebral hypoxia (brain not examined), large defect coronary sinus to left atrium
15	F, 3	6-17-57	III D	+	PS, septal defect?	ASD, PS, MS?	Valv and inf PS, ASD, MS	0	0	Collapse left lung, progressive hypoxia, tachycardia and ventricular fibrillation, massage and defibrillation could not establish effective cardiac action
16	M, 2	9-25-57	II C	+	Transposition and VSD or single vent	ASD, r vent hypt, PS?		18		Severe arterial hypoxemia before and during procedure, cyanosis progressed afterward and patient died of hypoxia
17	M, 9/12	10-21-57	IV D	+	Cyanotic CHD	VSD, inf PS	VSD, inf PS, FO	11	0	Pulmonary edema, two selective angiograms made

* This table was compiled from material gathered by Drs H F Helmholz, Jr and J E Edwards

† Abbreviations MS = mitral stenosis, MI = mitral insufficiency, CHD = congenital heart disease, CHF = congestive heart failure AI = aortic insufficiency, VSD = ventricular septal defect, ASD = atrial septal defect, PDA = patent ductus arteriosus, PS = pulmonary stenosis, hypt = hypertension, PAVC = persistent atrioventricular canal, LSVC = persistent left superior vena cava, vent = ventricle, inf = infundibular, FO = valve-competent foramen ovale, RHD = rheumatic heart disease

TABLE 4-38. PREDOMINANT DEFECTS IN 100 CONSECUTIVE PATIENTS UNDERGOING RIGHT HEART CATHETERIZATION

Diagnosis	Frequency, no of patients
Normal	3
[illegible]	2
[illegible]	3
[illegible]	2 *
[illegible]	20
[illegible]	3 †
[illegible]	24
Plus an additional lesion	9 ‡
Ventricular septal defect plus pulmonary stenosis (tetralogy of Fallot)	11 §
Common atrioventricular canal	4
Mitral or aortic valvular disease	7 ¶
Miscellaneous	9 *

[illegible]

cleared completely in both instances; the third experienced temporary nausea and confusion during the procedure, these symptoms were associated with ankle clonus and a Babinski sign Two patients showed evidence consistent with coronary embolism. One of these, already discussed, died soon after termination of the procedure. One patient experienced thoracic pain, syncope, and hypotension after completion of the procedure, she died 8 days later after surgical correction of an atrial septal defect and was found to have a myocardial infarct the character of which indicated that it had occurred several days prior to death Three patients had transient symptoms of abdominal pain compatible with embolic obstruction of an artery.

No evidence has been obtained in this series of cases relating the occurrence of pulmonary infarction to the procedure of wedging a catheter in a pulmonary artery.

PYROGENIC REACTIONS Experience indicates that these reactions can be avoided almost completely if proper care is exerted in cleansing and rinsing the catheter lumens and the intraarterial blood-sampling assemblies immediately after their use. Care also must be exercised in the proper cleansing of the infusion assemblies used to fill and flush the catheter and needle assemblies with sterile isotonic solutions and in the handling of these solutions. Use of commercially packaged sterile Ringer's solution for intravenous injection is recommended for this purpose.

THROMBOPHLEBITIS Some degree of thrombophlebitis of the vein through which the catheter is inserted is common after cardiac catheterization. Serious sequelae such as pulmonary infarction resulting from thrombophlebitis have not been observed in this series of patients.

Fatality Rate in Cardiac Catheterization Associated with General Anesthesia. It is difficult to interpret the significance of the fatality rate associated with diagnostic right heart catheterization because a number of factors other than the procedure itself affect this figure. Among these are the severity of the heart disease in patients selected for cardiac catheterization and the age of the patients, particularly in relation to whether anesthesia is required. Most of the patients in this series had severe heart disease, as evidenced by the fact that a number of patients for whom appointments for catheterization had been made died in the waiting period before the appointment.

General anesthesia was used in 348 procedures carried out on small children and infants. One death, already discussed, occurred (in this series of children) during cardiac catheterization, as a result of ventricular tachycardia and ensuing ventricular fibrillation preceded by hypoxia associated with collapse of a lung. Ten deaths, however, occurred in these children in the period from 6 to 24 hr after completion of the procedure, as compared to only two deaths in this same period in the 1,362 adults and older children on whom catheterization was performed without anesthesia. This striking difference in fatality rate presumably is related to the added risk associated with anesthesia in small children and infants who have severe heart disease, and to the fact that the underlying heart disease was generally more severe in the younger age groups.

The possibility that selection of patients or relatively minor changes in the conduct of the anesthesia and postcatheterization care may have a striking effect on the fatality rate should always be considered.

SUCCESS RATE OF MODERN DIAGNOSTIC CARDIAC CATHETERIZATION

In order to obtain an accurate idea of what the usual diagnostic cardiac catheterization at the Mayo Clinic consists of and how successful such a procedure is in establishing an accurate diagnosis, H. W Marshall analyzed in detail 100 consecutive right heart catheterizations carried out by Wood during the period from July, 1955, through June, 1956 The age of this series of patients ranged from 7 weeks to 71 years General anesthesia was used in 58 of these patients because they were infants or small children, these 58 patients had an average age of 3 8 years, with a range of 2 months to 13½ years.

The complexity and difficulty of establishing a diagnosis by right heart catheterization are re-

TABLE 4-39 AVERAGE AND RANGE OF COMPONENT PORTIONS OF 100 CONSECUTIVE DIAGNOSTIC RIGHT HEART CATHETERIZATIONS *

	Fluoroscopic time, min	Number of roentgenograms	*Number of blood samples for analysis* Cuvette oximetry	Van Slyke method	Number of dye curves	Duration of procedure, min	Number of photokymographic records †
Average	10.2	7 6	26	4.6	5	178	44
Range	2-23	0-18	10-49	0-19	0-11	90-290	32-68

dilution curves.

lated to the complexity of the anatomical defect or defects and the hemodynamic aberrations present in these patients. The anatomical defects encountered in these 100 patients are listed in Table 4-38 Table 4-39 provides information concerning the average magnitude and range of various components of a diagnostic catheterization procedure and hence the extent of the usual procedure carried out at Mayo Clinic.

In 92 of these procedures, determinations of intracardiac pressure, blood flow, and other variables were made both when the patient was breathing air and when he was breathing 99 5 per cent oxygen. *In 54 of the procedures, those in which the physician considered that the study could be extended without risk to the patient, additional observations* were made in conjunction with various investigative projects, such as studies of the effects on dilution curves of the indicator used, the dose injected, and the manner of its injection.

The degree of success of these catheterization procedures in establishing a diagnosis *of the cardiovascular* pathological changes present has been graded on the basis of 0 to 4 The criteria for *placing* individual cases in these five grades are listed in Table 4-40.

The incidence of the various degrees of success in these 100 consecutive cardiac catheterizations separated on the basis of age is listed in Table 4-41

Data of practical *diagnostic importance* were obtained during each of these 100 procedures These data were considered sufficiently complete to *establish the diagnosis* with certainty and to allow the prognosis, disposition, and treatment to be determined in 60 per cent of these cases In 97 per cent *of the procedures*, the data were considered adequate to establish the diagnosis but some data required for completion of proper prognosis, disposition, or delineation of therapy were lacking As might be expected, the incidence of 13 per cent of the procedures failing to establish

TABLE 4-40 CRITERIA FOR GRADING DEGREE OF SUCCESS OF RIGHT HEART CATHETERIZATION

Grade of success	*Criterion*
0	No data obtained not available by simpler measures
1	
2 *	[illegible] importance but not sufficient for any definite diagnosis or to suggest treatment
3 †	Data for diagnosis obtained but some essential data lacking for completeness
4	[illegible] treatment

* Example· Right ventricular *pressure* increased but pulmonary arterial pressure, or other data sufficient to provide reason for right ventricular hypertension, not obtained

† Example Arterialization demonstrated at right atrial level but no data, such as right and left pul- [illegible] ves, [illegible] due [illegible] pulmonary venous connection, persistent atrioventricular canal, or other causes.

TABLE 4-41. ACCURACY OF CLINICAL AND CARDIAC CATHETERIZATION DIAGNOSES

(based on surgical or necropsy findings in 47 patients *)

Grading of accuracy of diagnosis	Per cent of cases	
	Clinical diagnosis	Catheterization diagnosis
Complete and correct	47	77
Two diagnoses suggested, one of which was complete and correct	23	4
Correct but incomplete	11	11
Partially correct and partially incorrect .	17	8
Incorrect . .	2	0

* Final diagnosis based on necropsy in 13 of these patients and on surgical findings in 34

a diagnosis (grade 2 success) in infants less than 1 year of age was considerably greater than the incidence of less than 2 per cent for grade 2 success in the groups more than 1 year of age.

Subsequent to cardiac catheterization, 47 of these 100 consecutive patients underwent surgical correction of their cardiac lesions[15] or were examined at necropsy at some later date One child (Table 4-37, case 10) died 18 hr after the catheterization procedure was completed The correlation between the clinical diagnosis, the diagnosis based on the findings at cardiac catheterization, and the final diagnosis based on the findings at operation or necropsy is shown in Table 4-41

It is to be anticipated that cardiac catheterization would provide a greater percentage of complete and accurate diagnoses than that possible by clinical methods (including electrocardiography and roentgenographic examination) alone Of practical importance is the finding that this series of cases included no instances of a completely incorrect diagnosis and less than 10 per cent of partially incorrect diagnoses after cardiac catheterization, as compared to an incidence of approximately 20 per cent in these two categories of error in the diagnoses established by clinical methods alone.

When auxiliary techniques such as cuvette oximetry and selective indicator-dilution curves are not used, right heart catheterization frequently fails to provide sufficiently complete information to establish the diagnosis and prognosis, as well as the basis for deciding on the disposition and treatment of a given patient with congenital heart disease. The frequency of failure to obtain complete information by right heart catheterization without auxiliary techniques is suggested by the fact that 23 of these 100 patients had undergone right heart catheterization previously at other institutions and the available data were not considered sufficient to allow a decision to be made as to the disposition of these patients. Three of the patients had been catheterized twice, and one three times, prior to their study at the Mayo Clinic. The right heart catheterizations performed in the authors' laboratory on these 23 patients were considered to be completely successful in 19 cases, in the remaining four, the information obtained was considered adequate to establish the diagnosis, but some data required for completeness of proper prognosis, disposition, or delineation of treatment were lacking.

[15] Open-heart operations were done on forty of these patients and closed-heart operations on four.

RADIATION EXPOSURE

Right heart catheterization entails an exposure to x-rays that represents a significant hazard to both the patient and the persons doing the catheterization. Every effort should be made to keep the x-ray exposure time to a minimum during each procedure Likewise, it is at least equally as important that the body area viewed by the fluoroscope be kept as small as possible during manipulation of the catheter under fluoroscopic control Use of the smallest possible fluoroscopic field not only reduces greatly the total radiation received by the patient per minute of fluoroscopic time but also reduces to an even greater degree the amount of scattered radiation from the patient to which the catheterization team is exposed. This exposure to scattered radiation constitutes a real hazard to the long-term health of all cardiac catheterization teams. All means of protective shielding of the x-ray tube and shielding against scattered radiation from the patient that do not result in a practically important degree of interference with the conduct of the procedure should be considered an absolute necessity. In addition, all persons working in the immediate vicinity of the patient should wear protective lead-containing aprons or, preferably, special clothing designed to protect a larger portion of the body surface, particularly those regions subjected to the greatest radiation. The accumulated radiation exposure of persons doing right heart catheterization routinely should be monitored by film badges or other suitable means, and careful records of this information should be kept. These data shou

persons w

radiation, ...

ing exposure is kept below currently accepted safe limits.

Radiation Exposure of Patient. In the authors' laboratory, the maximum fluoroscopic time allowed for diagnostic cardiac catheterization is 20 min. The actual time required varies greatly among different patients and is determined by the complexity of the malformations present and the degree of difficulty encountered in manipulating the catheter tip into the desired positions in the heart and great vessels. The average fluoroscopic time required for diagnostic right heart catheterization in this laboratory is approximately 10 min. On the average, the x-ray tube is operated at 73 kv and 3 ma, which gives an exposure of 6.7 r/min measured in air at the surface of the mattress that comes in contact with the patient's back. Changing this mattress from one of sponge rubber to one of polyvinyl plastic sponge increased the rate of exposure measured in air at the upper surface of the mattress from 4.0 to 6.7 r/min when the x-ray tube was operated at identical voltage and amperage.

Radiation Exposure of Catheterization Team. Studies of the radiation exposure of the persons performing cardiac catheterization in the authors' laboratory have been made through the cooperation of A. Orvis (Sect. Biophysics, Mayo Clinic) using the film-badge technique. The film badges were worn outside the protective clothing (lead aprons) over the left upper part of the thorax. This is a region that is in close proximity to the patient and the x-ray beam when the catheter is being manipulated under fluoroscopic control and is, therefore, a portion of the body considered to be exposed to a relatively high exposure (during this procedure) in relation to other body areas.

Figure 4-170 shows the accumulated film-badge

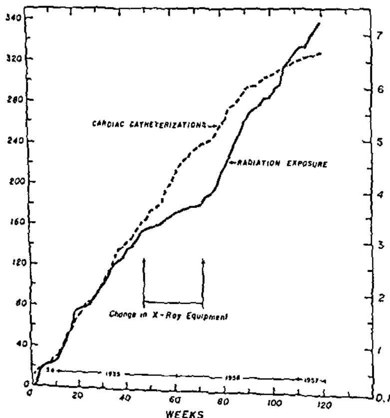


Fig. 4-170. Accumulated exposure to roentgen radiation by a physician performing 325 cardiac catheterizations over a period of 120 weeks. Note the striking decrease in rate of exposure coincident with the period, delineated by arrows, during which a different x-ray tube, shutter mechanism, and mount were used. Note also that the total accumulated exposure by the physician is approximately equal to that received by a patient undergoing cardiac catheterization when the fluoroscope is used for only 1 min.

exposure for one of the authors (Wood) after performing diagnostic cardiac catheterization over a period of 120 weeks. The importance of the x-ray equipment used, *in minimizing exposure to scattered radiation, is indicated by the striking decrease* in exposure per minute of fluoroscopic time that occurred during the period when the mounting, shutter mechanism, and type of x-ray tube on the fluoroscopic table were changed. Concomitant with this change, the rate of radiation exposure to *the person performing cardiac catheterization with* this equipment decreased from approximately 5 mr/min of fluoroscopic time to 0.9 mr/min, returning to the previous level when the tube and mounting were changed again.

The rate of accumulation of radiation exposure *by the personnel who perform cardiac catheterization* in the Mayo Clinic exceeds that *found for* that institution's diagnostic radiologists. The apparently higher incidence of leukemia found in radiologists suggests that this rate of radiation exposure may be a significant hazard to those doing cardiac catheterization.

Apparently the radiation hazard to the cardiac catheterization team and to the patient cannot be reduced further by protective measures that do not entail a significant hindrance to the conduct of the procedure The evident solution to this problem is the use of *equipment to amplify the image on* the fluoroscopic screen, which allows adequate visualization of the cardiac catheter with a great decrease in the radiation required Commercially available image intensifiers have proved feasible for this purpose

SUMMARY

The clinical signs and symptoms associated with the commoner types of congenital and acquired heart disease have become sufficiently well recognized in recent years so that a skilled cardiologist by means of clinical examination, including electrocardiography and roentgenographic studies, can establish the diagnosis with certainty without the necessity of right heart catheterization. *Exclusive of the need for investigative studies,* cardiac catheterization *for* diagnostic purposes in the majority of instances can be reserved, therefore, for (1) patients with mild congenital or acquired heart disease, in whom the symptoms and signs are not sufficiently well developed to make possible a certain decision as to whether or not a significant cardiac abnormality is present, or (2) patients with complicated congenital heart disease, in whom a definitive diagnosis cannot be arrived at by simpler methods.

When diagnostic right heart catheterization *is undertaken under these circumstances,* it *should be anticipated that a complex procedure may be required in order* to establish a diagnosis and the hemodynamic *status in* a given patient. Successful execution of such a procedure requires a team of persons who have intimate knowledge of the anatomy and hemodynamics of congenital and acquired heart disease and a long experience in cardiac catheterization and associated procedures. To perform successfully, this cardiac catheterization team requires a fully equipped laboratory and a kymographic recording assembly capable, among other things, of providing *immediate determinations of blood oxygen* saturation, *simultaneous pressure recordings from multiple sites in the cardiovascular system,* continuously recorded indicator-dilution curves, and facilities for selective angiocardiography. To attain a reasonably high rate of success in cardiac catheterization, it is essential that the information obtained by these methods be available to the catheterization team as the measurements are being made, since *these* data are required *to* determine how the *procedure should be varied or extended in order* to obtain *the pertinent information* required to establish the diagnosis and evaluate the hemodynamic status

Cardiac catheterization performed in this manner has better than a 95 per cent chance of success in establishing a diagnosis in a single procedure. It is *impossible to* overemphasize the importance, from both the humanitarian and *economic* points of view, of *carrying out cardiac* catheterization in a manner and with equipment that minimize chances of failure and the consequent necessity of repeated or additional procedures for an adequate diagnosis.

LEFT HEART CATHETERIZATION

Ordinary *clinical* methods may usually be *relied upon in* the diagnosis of typical valvular defects. Left heart catheterization is not performed as a routine procedure in order to confirm a clear diagnosis The authors have introduced left heart catheterization with pressure

measurements in the left atrium, the left ventricle, and aorta, calculating the pressure gradients in the aortic and mitral orifices, in cases with combined lesions which are difficult to evaluate. The goal has been the proper selection of patients for surgical treatment.

The following problems indicate the need for left heart catheterization:

1 When mitral stenosis and insufficiency are combined, which is predominant?

2. Is there a combination of mitral and aortic valvular disease?

3 How severe is aortic stenosis, how early can it be diagnosed?

After evaluating the pressure gradients obtained at left heart catheterization, the authors may advise selective angiocardiography with injection of contrast medium in the left atrium or ventricle. These investigations are performed in order to outline anatomically the mitral and aortic orifices, and the movements and flexibility of these valves.

During left heart catheterization, one sign has been of special value, i.e., when the thin plastic catheter is repeatedly thrown back into the left atrium *from* the left ventricle after a few heart beats. This finding speaks in favor of a significant mitral regurgitation

TECHNIQUE

The transbronchial route for puncture of the left atrium was first developed by Facquet et al (1952) In 1953, Bjork and coworkers developed the posterior percutaneous puncture technique This method was the first to be de- [illegible] er [illegible] id [illegible] ven-tricle and the aorta Thus, it was possible to determine the presence or absence of abnormal pressure gradients across both the aortic and mitral valves Radner has developed an anterior suprasternal technique for the puncture of the left atrium

The principal advantages of the posterior percutaneous puncture method are that (1) one can obtain left ventricular pressure, and (2) one can perform selective angiocardiography with injection of contrast medium into the left atrium.

The procedure is as follows.

The patient is usually given no premedication, but slight sedation may be preferable. On completion of right heart catheterization, a needle or catheter is introduced into a systemic artery. The rate of oxygen uptake of the patient is determined by the open-circuit method and samples of blood are withdrawn simultaneously from the pulmonary and systemic arteries for determination of cardiac output by the direct Fick method.

The patient is then rotated forward to lie on his left side. The puncture may be performed in any position from prone to lateral, lying on the left side If angiocardiography is to be performed, an optimum position (lying on the left side tilted 30 to 40° forward) is chosen, otherwise the lateral position should be used

The patient is fluoroscoped in the morning before the catheterization and indicators are placed anteriorly and posteriorly over the left atrium. These make fluoroscopic control during the catheterization unnecessary. The site of the puncture is *at the upper border of the 9th rib, 6 to 7 cm to the right of the midline.* The needle is then introduced in a direction toward the anterior indicator (usually 3 fingerbreadths cranial to the lower end of sternum; Fig. 4-171).

The skin and underlying tissues are infiltrated with 0 5 per cent procaine (without Adrenalin) The needle, connected to a syringe, is then introduced, using slight aspiration. The needle is first advanced towards the vertebral body, then directed more to the right. The cardiac impulse can usually be felt via the needle before the tip is felt to pass through the pericardium and the wall of the left atrium. When the left atrium is entered, *bright-red blood is aspirated.* The oxygen content of left atrial blood is higher than that in a sample from a systemic artery. The left atrial pressure curve is obtained A thin plastic catheter is then introduced through the needle into the atrium and down into the left ventricle. It has always been possible to manipulate the catheter down into the left ventricle. However, it has not always been possible to manipulate the catheter out into the aorta If this cannot be done, the simultaneously obtained pressure curve from a systemic artery will be of the same diagnostic value in the determination of a pressure gradient across the aortic valve (Fig. 4-172A). If the catheter is repeatedly thrown back from the left ventricle into the atrium after a few heart beats, a significant regurgitation may be expected.

COMPLICATIONS

A certain risk always accompanies a puncture of the heart. According to the authors' experience, a puncture of the left atrium is followed by more complications than one of the left ventricle In the authors' material, it is obvious that the complications after puncture of

exposure for one of the authors (Wood) after performing diagnostic cardiac catheterization over a period of 120 weeks. The importance of the x-ray equipment used, in minimizing exposure to scattered radiation, is indicated by the striking decrease in exposure per minute of fluoroscopic time that occurred during the period when the mounting, shutter mechanism, and type of x-ray tube on the fluoroscopic table were changed. Concomitant with this change, the rate of radiation exposure to the person performing cardiac catheterization with this equipment decreased from approximately 5 mr/min of fluoroscopic time to 0.9 mr/min, returning to the previous level when the tube and mounting were changed again.

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During left heart catheterization, one sign has been of special value, i e, when the thin plastic catheter is repeatedly thrown back into the left atrium from the left ventricle after a few heart beats. This finding speaks in favor of a significant mitral regurgitation

TECHNIQUE

The transbronchial route for puncture of the left atrium was first developed by Facquet et al (1952) In 1953, Bjork and coworkers developed the posterior percutaneous puncture technique This method was the first to be developed for passing a small plastic catheter through the needle into the left atrium and then advancing this catheter into the left ventricle and the aorta Thus, it was possible to determine the presence or absence of abnormal pressure gradients across both the aortic and mitral valves Radner has developed an anterior suprasternal technique for the puncture of the left atrium

The principal advantages of the posterior percutaneous puncture method are that (1) one can obtain left ventricular pressure, and (2) one can perform selective angiocardiography with injection of contrast medium into the left atrium.

The procedure is as follows.

The patient is usually given no premedication, but slight sedation may be preferable On completion of right heart catheterization, a needle or catheter is introduced into a systemic artery. The rate of oxygen uptake of the patient is determined by the open-circuit method and samples of blood are withdrawn simultaneously from the pulmonary and systemic arteries for determination of cardiac output by the direct Fick method.

The patient is then rotated forward to lie on his left side The puncture may be performed in any position from prone to lateral, lying on the left side. If angiocardiography is to be performed, an optimum position (lying on the left side tilted 30 to 40° forward) is chosen, otherwise the lateral position should be used.

The patient is fluoroscoped in the morning before the catheterization and indicators are placed anteriorly and posteriorly over the left atrium. These make fluoroscopic control during the catheterization unnecessary. The site of the puncture is *at the upper border of the 9th rib, 6 to 7 cm to the right of the midline*. The needle is then introduced in a direction toward the anterior indicator (usually 3 fingerbreadths cranial to the lower end of sternum, Fig 4-171).

The skin and underlying tissues are infiltrated with 0 5 per cent procaine (without Adrenalin). The needle, connected to a syringe, is then introduced, using slight aspiration. The needle is first advanced towards the vertebral body, then directed more to the right. The cardiac impulse can usually be felt via the needle before the tip is felt to pass through the pericardium and the wall of the left atrium When the left atrium is entered, bright-red blood is aspirated. The oxygen content of left atrial blood is higher than that in a sample from a systemic artery. The left atrial pressure curve is obtained A thin plastic catheter is then introduced through the needle into the atrium and down into the left ventricle It has always been possible to manipulate the catheter down into the left ventricle However, it has not always been possible to manipulate the catheter out into the aorta. If this cannot be done, the simultaneously obtained pressure curve from a systemic artery will be of the same diagnostic value in the determination of a pressure gradient across the aortic valve (Fig. 4-172A). If the catheter is repeatedly thrown back from the left ventricle into the atrium after a few heart beats, a significant regurgitation may be expected.

COMPLICATIONS

A certain risk always accompanies a puncture of the heart According to the authors' experience, a puncture of the left atrium is followed by more complications than one of the left ventricle. In the authors' material, it is obvious that the complications after puncture of

exposure for one of the authors (Wood) after performing diagnostic cardiac catheterization over a period of 120 weeks. The importance of the x-ray equipment used, in minimizing exposure to scattered radiation, is indicated by the striking decrease in exposure per minute of fluoroscopic time that occurred during the period when the mounting, shutter mechanism, and type of x-ray tube on the fluoroscopic table were changed. Concomitant with this change, the rate of radiation exposure to the person performing cardiac catheterization with this equipment decreased from approximately 5 mr/min of fluoroscopic time to 0.9 mr/min, returning to the previous level when the tube and mounting were changed again.

The rate of accumulation of radiation exposure by the personnel who perform cardiac catheterization in the Mayo Clinic exceeds that found for that institution's diagnostic radiologists. The apparently higher incidence of leukemia found in radiologists suggests that this rate of radiation exposure may be a significant hazard to those doing cardiac catheterization.

Apparently the radiation hazard to the cardiac catheterization team and to the patient cannot be reduced further by protective measures that do not entail a significant hindrance to the conduct of the procedure. The evident solution to this problem is the use of equipment to amplify the image on the fluoroscopic screen, which allows adequate visualization of the cardiac catheter with a great decrease in the radiation required. Commercially available image intensifiers have proved feasible for this purpose.

SUMMARY

The clinical signs and symptoms associated with the commoner types of congenital and acquired heart disease have become sufficiently well recognized in recent years so that a skilled cardiologist by means of clinical examination, including electrocardiography and roentgenographic studies, can establish the diagnosis with certainty without the necessity of right heart catheterization. Exclusive of the need for investigative studies, cardiac catheterization for diagnostic purposes in the majority of instances can be reserved, therefore, for (1) patients with mild congenital or acquired heart disease, in whom the symptoms and signs are not sufficiently well developed to make possible a certain decision as to whether or not a significant cardiac abnormality is present, or (2) patients with complicated congenital heart disease, in whom a definitive diagnosis cannot be arrived at by simpler methods.

When diagnostic right heart catheterization is undertaken under these circumstances, it should be anticipated that a complex procedure may be required in order to establish a diagnosis and the hemodynamic status in a given patient. Successful execution of such a procedure requires a team of persons who have intimate knowledge of the anatomy and hemodynamics of congenital and acquired heart disease and a long experience in cardiac catheterization and associated procedures. To perform successfully, this cardiac catheterization team requires a fully equipped laboratory and a kymographic recording assembly capable, among other things, of providing immediate determinations of blood oxygen saturation, simultaneous pressure recordings from multiple sites in the cardiovascular system, continuously recorded indicator-dilution curves, and facilities for selective angiocardiography. To attain a reasonably high rate of success in cardiac catheterization, it is essential that the information obtained by these methods be available to the catheterization team as the measurements are being made, since these data are required to determine how the procedure should be varied or extended in order to obtain the pertinent information required to establish the diagnosis and evaluate the hemodynamic status.

Cardiac catheterization performed in this manner has better than a 95 per cent chance of success in establishing a diagnosis in a single procedure. It is impossible to overemphasize the importance, from both the humanitarian and economic points of view, of carrying out cardiac catheterization in a manner and with equipment that minimize chances of failure and the consequent necessity of repeated or additional procedures for an adequate diagnosis.

LEFT HEART CATHETERIZATION

Ordinary clinical methods may usually be relied upon in the diagnosis of typical valvular defects. Left heart catheterization is not performed as a routine procedure in order to confirm a clear diagnosis. The authors have introduced left heart catheterization with pressure

chamber, in a patient with a normal pressure in the left atrium When the patient made an unwanted deep inspiration, air was aspirated through the puncture needle into the left heart. There was a complete restitution and, after 2 hr, the left ventricle was punctured

Once a catheter was cut against the sharp edge of a needle while it was being withdrawn from the left atrium. At another occasion, two plastic catheters were used, one in the left atrium and one in the left ventricle while the patient was doing an exercise test. These two catheters made a knot around the papillary muscle and could not be freed from each other In both cases, cardiotomy was performed to take out the catheters and, at the same time, perform a mitral valvulotomy. Both patients made an uneventful recovery. Without any doubt, the number of complications encountered is considerable. It does, however, include all the early errors made while the method was worked out and evaluated Many of these errors can now be avoided as a result of accumulated experience Therefore, the authors recommend the following precautions for percutaneous left atrial puncture

1 A diagnostic puncture of the left heart should be carried out only by a thoracic surgeon, and only in the presence of an anesthesiologist and a cardiologist

2 All equipment necessary for an immediate thoracotomy should be present in the room A cardiac defibrillator should be at hand, connected, and ready for use

3 Perfect anesthesia is very important during selective left-sided angiocardiography. The anesthetist should be experienced in giving anesthesia to patients with severe heart disease, since this investigation is mostly indicated in patients with severe heart disease.

4 Not more than two punctures of the left atrium should be allowed in the same sitting As there is no reason to perform left atrial puncture unless the left atrium is enlarged, it is easy to puncture this chamber at the first introduction of the needle.

5. There must be no leakage in the connections between the puncture needle and the pressure transducer, or between the needle and pressure syringe used in selective angiocardiography

6 It is not advisable to use two catheters simultaneously in the left side of the heart, it is far better to use one needle and one catheter

7. When one wishes to withdraw the catheter introduced through the needle in the left atrium, it is better to first withdraw the needle and then the catheter. Following this technique, there is no possibility of cutting the catheter against the sharp edge of the needle.

8. Because the kidney is sensitive to the iodine-containing contrast solutions, it is necessary to control the urine output and the nonprotein nitrogen for the first week after an angiocardiography. A new angiocardiography should not be performed on the same patient unless a time interval of at least 2 weeks has elapsed Otherwise, there will be considerable risk of lasting damage to the kidneys.

RESULTS

The authors have punctured the left atrium, with or without catheterization of the left ventricle, in 167 patients. They have directly punctured the left ventricle in 31 patients. They have performed selective angiocardiography in connection with a puncture of the left atrium in 50 patients, and in connection with a puncture of the left ventricle in 30 patients. One hundred and five patients have then undergone valvulotomy, two patients have been autopsied without prior surgery The value of left heart catheterization has been judged in these 107 patients where the underlying anatomical changes have been confirmed

Furthermore, the authors have punctured the left atrium for pressure measurements on a subject with normal valves and, in another case, they have performed an angiocardiography in the left atrium on a subject with normal valves As these investigations are accompanied by a certain risk, it has naturally not been possible to obtain a larger number of normal subjects for comparison

It has sometimes been impossible to introduce the plastic catheter from the left atrium into the left ventricle This has been repeatedly observed in cases of significant mitral regurgitation. When the catheter has been passed through the mitral orifice into the left ventricle, series of extrasystoles and attacks of tachycardia have been observed as long as the catheter was within the ventricle During the periods of arrhythmia, it was difficult to obtain representative diastolic pressure levels in the left ventricle In cases where it was difficult or impossible to push the catheter further out into the aorta through the aortic orifice, the authors used instead a comparison of simultaneous tracings from the brachial artery and

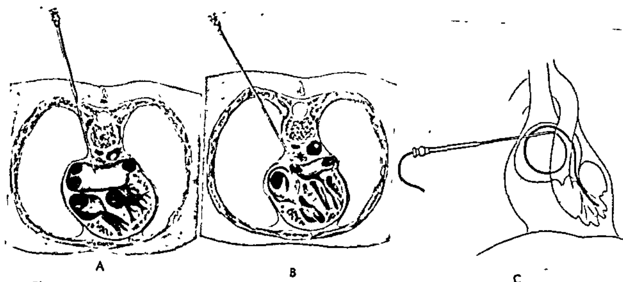


Fig. 4-171. A. It is easy to introduce the needle into an enlarged left atrium from a puncture site 5 to 6 cm to the right of the midline at the upper border of the 9th rib posteriorly. B. In case the left atrium is small, it is necessary to move the needle more laterally and through the lung tissue. In cases of aortic valvular stenosis, direct puncture of the left ventricle may be preferred. C. A thin plastic catheter is introduced through the needle, through the left atrium, into the left ventricle, and then into the aorta.

a small left atrium in cases of aortic valvular disease have been considerably more numerous than with an enlarged left atrium because of mitral valvular disease.

The following complications have been encountered after puncture of the left atrium in 167 investigations.

	Mitral	*Aortic*
Cardiac tamponade with ventricular fibrillation		2
Transient ventricular fibrillation	1	
Transient heart standstill	1	
Transient hemiplegia	1	
Hemothorax (350 ml)	1	
Pneumonia	1	1
Pneumonia and pericarditis	2	
Catheter complications	2	
Wrong contrast injection	2	
Total	11	3
Number of cases	150	17
Major complications, per cent	7 3	17 6

Puncture of the left ventricle, on the other hand, has given only one complication in 30 investigations, and that was minor At the time the needle was introduced into the left ventricle, severe electrocardiographic changes of the left ventricular wall were observed in a case with combined aortic and mitral lesions Respiration and blood pressure were not altered during the investigation which, however, was terminated. The needle was withdrawn and in a few minutes the electrocardiogram was normal. The investigation was repeated, with introduction of a needle into the left ventricle and selective angiocardiography, two weeks later without complications.

Discussion of Complications. Of the two patients with *cardiac tamponade* and *ventricular fibrillation*, one had luetic aortitis with a large aortic aneurysm. The authors thought it would be possible to introduce the needle lateral to the aneurysm. However, it was very large and compressed the left atrium in an anteroposterior direction, resulting in a very small lumen of the left atrium in the direction of the needle. The needle, therefore, passed through the left atrium into the root of the thin aortic wall causing bleeding and tamponade, since this wall had no elasticity. In this patient, exploration was made, and a skin graft had to be wrapped around the aorta over the puncture hole. The patient, however, died later from brain damage.

In the case of the second patient, who had aortic stenosis, the left atrium was entered in a normal way. However, due to technical error, the pressure tracings obtained showed a too low pressure and therefore the needle was withdrawn and introduced again The procedure was repeated several times, always revealing low pressure. The bleeding through several puncture holes caused *cardiac tamponade* The patient was resuscitated and a transventricular aortic valvulotomy was performed, the patient recovered but died a month later.

In the patient with the transient ventricular fibrillation there was an impaired ventilation after anesthesia As soon as the electrocardiogram was observed, the patient was intubated and ventilated; then, a normal tracing was obtained.

The transient hemiplegia was caused by air embolism, due to a faulty connection between the puncture needle and the tube to the pressure

chamber, in a patient with a normal pressure in the left atrium. When the patient made an unwanted deep inspiration, air was aspirated through the puncture needle into the left heart. There was a complete restitution and, after 2 hr, the left ventricle was punctured

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the left ventricle, in order to compare the levels of systolic pressures.

Comparison of Left Heart Catheterization with Other Investigations and with the Surgical Findings. The pressure in the left atrium has practically always been of the same magnitude as the pressure in the pulmonary capillaries Sometimes, however, the pulmonary capillary pressure has been found to be higher than the pressure in the left atrium (Fig. 4-172B). This

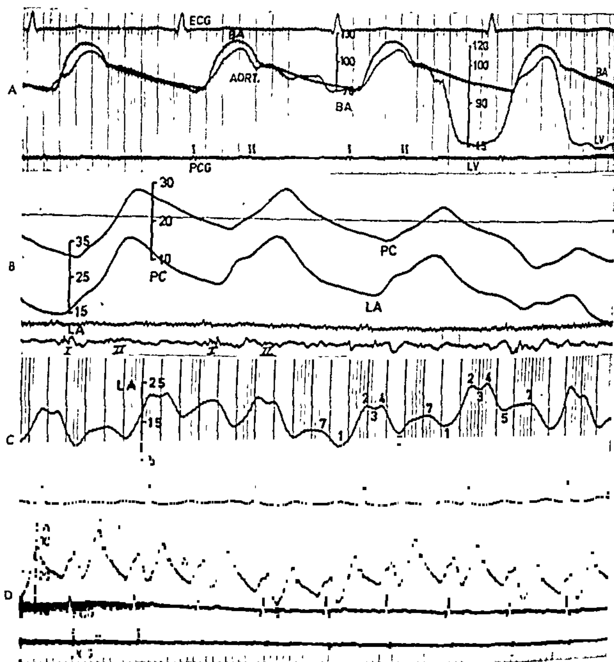
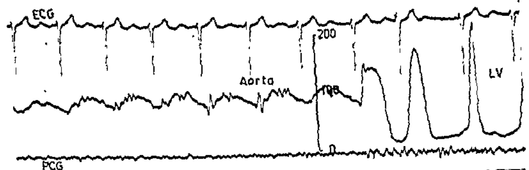


Fig. 4-172. A The simultaneously obtained brachial artery pressure curve will be of the same diagnostic value as a pressure tracing from the aorta in the determination of a pressure gradient across the aortic valves This demonstrates a simultaneous pressure tracing from the brachial artery (BA) and the withdrawal curve from the aorta into the left ventricle (LV). The systolic pressure peaks are of the same magnitude. B The pressure in the left atrium (LA) has been practically always of the same magnitude as the pressure measured in the pulmonary capillaries (PC). Furthermore, the configuration of the pressure curve in the left atrium is very well reflected in the pulmonary capillaries. C. In cases with sinus rhythm, a significant presystolic pressure rise (1-2-3-4-5) is observed in the left atrium (LA) D A left atrial pressure curve from a patient with pure mitral stenosis. In this curve, the presystolic pressure peak is not dominant. At operation, no signs of mitral insufficiency were found.

A



C

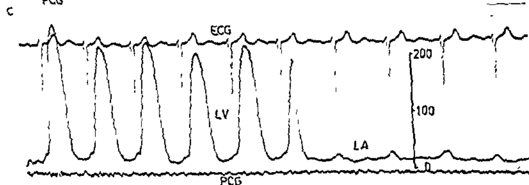


Fig. 4-173 A In this case of pure mitral stenosis, a diastolic *pressure gradient* of approximately 15 mm Hg between the left atrium (LA) and the left ventricle (LV) *is seen in the* withdrawal curve from the left *ventricle to the left* [illegible] left *atrial* [illegible] from the [illegible] gradient [illegible] mm Hg. The continued withdrawal curve from the left ventricle (LV) to the left atrium (LA) fails to show any *gradient*. The mitral valve was normal.

may be explained by an erroneous position of the catheter when the increased pressure observed is due to anastomosing bronchial arteries or to the pulmonary artery. Sometimes the authors have also observed a different configuration of the left atrial pressure curve as compared to the pulmonary-capillary pressure curve. This has probably the same explanation of a bad position of the heart catheter in the pulmonary artery.

In cases of *pure mitral stenosis* the following observations were made:

1. The pressure in the left atrium is practically always higher than normal pressure at rest.

2. In a few cases, there has been a normal left atrial pressure in spite of mitral stenosis.

3. In cases with sinus rhythm, there is a significant *presystolic pressure rise* in the left atrium. This pressure peak may dominate the configuration of the left atrial pressure curve Its descending limb is often kinked, as described by Radner (Fig 4-172C and D).

4. In most cases, *a positive diastolic pressure gradient* has been observed between the left atrium and the left ventricle This gradient may correspond to a pressure difference of more than 20 mm Hg (Fig 4-173A)

5. The pressure level during diastole is normal in the left ventricle

6. Selective angiocardiography of the left atrium will often visualize the thickness and mobility of the mitral valves and sometimes the opening of the mitral orifice. The size of the left atrium, its form, and its variations in volume during the cardiac cycle, as well as the presence of thrombi in the left atrium, may be visualized by means of selective angiocardiography.

In cases of *pure mitral insufficiency* (there were only two such cases), the authors have observed that:

1. The pressure in the left atrium was high

2. There was no pressure gradient in diastole between the left atrium and the left ventricle (in the case which was investigated).

3. No marked presystolic pressure peak existed in the left atrial pressure curve This curve is dominated by a *systolic pressure peak* having a rounded descending limb (Fig. 4-173B).

4. Selective angiocardiography of the left atrium will show a normal or enlarged mitral orifice in cases of pure mitral insufficiency.

5. Selective angiocardiography of the left ventricle will demonstrate the magnitude of regurgitation into the left atrium

In cases of *aortic valvular stenosis*, the authors have observed:

1. The pressure in the left ventricle will slowly increase to very high systolic values with a positive *systolic pressure gradient* between the left ventricle and the aorta. This pressure gradient is only found in cases with a high degree of stenosis (Fig. 4-173C).

2 A not-so-pronounced aortic valvular stenosis can be demonstrated by selective angiocardiography of the left ventricle. It is then possible to study the aortic leaflets, the thickness of the valves, and the fusion to a valvular dome. It is also possible to see the exact position of the aortic orifice and size of the left ventricle in systole and diastole and the thickness of the left ventricular wall.

GASES IN THE BLOOD

Blood normally contains large amounts of oxygen and carbon dioxide which are chemically combined with hemoglobin. It also contains small, but significant, amounts of oxygen, carbon dioxide, and nitrogen, which are dissolved in the blood The normal content of oxygen and carbon dioxide in arterial and mixed venous bloods, as well as the oxygen saturation, are shown in Table 4-42.

Determination of the oxygen and carbon dioxide content of the blood gives invaluable information for diagnosis, treatment, and prognosis of some of the cardiac and cardiopulmonary diseases Arterial oxygen saturation is obtained from the determination of *arterial oxygen content* and oxygen capacity. Arterial unsaturation can be detected by the use of these methods long before the clinical appearance of cyanosis, because cyanosis becomes noticeable only when 5 Gm of reduced hemoglobin are present in the capillary blood, corresponding to 80 per cent of arterial oxygen saturation in subjects with normal hemoglobin. Peripheral cyanosis, due to slower peripheral circulation, can also be detected because arterial saturation is normal in these cases.

Right heart catheterization permits one to obtain mixed "venous" blood from the pulmonary artery or right heart chambers and this, in turn, makes it possible to determine the arteriovenous oxygen difference. When oxygen consumption is determined simultaneously, cardiac output can be studied in man by using Fick's principle. This facilitates the study of the systemic and pulmonary circulations and the work done by the ventricles.

[illegible]

eas [illegible]

is [illegible] which relies upon accurate oxygen determination in various blood samples, obtained from the cardiac chambers and the large vessels. The resistance and size of the functional orifice of a stenotic pulmonic or tricuspid valve can also be calculated. Likewise, the functional orifice of a stenotic mitral or aortic valve can be accurately determined when simultaneous right and left heart catheterizations are performed.

Arterial or venous oxygen tension (P_{O_2}) and carbon dioxide tension (P_{CO_2}) in cardiopulmonary diseases can be calculated when the contents of these gases in the blood are determined and the pH of the blood is measured.

Blood oxygen can be determined by either chemical or physical methods. The most universally accepted chemical gasometric method is that of van Slyke and Neil. Other gasometric methods like that of Haldane (modified by Courtice and Douglas) and the micromethod of Roughton and Scholander may be used with satisfactory results. A physical measurement of the oxygen saturation of the blood can be made using the Millikan ear oximeter, modified by Wood et al. Another oximeter works through the so-called cuvette method (channel oximetry) by which the oxygen saturation of the whole blood can be determined spectrophotometrically. These electrophotometric methods give valuable results but are less accurate than chemical methods.

CLINICAL METHODS FOR MEASURING BLOOD OXYGEN CONTENT AND SATURATION

Principle of van Slyke-Neil (Gasometric) Determination of Oxygen. The gas, oxygen, which is physically dissolved or chemically combined with hemoglobin, is liberated chemically and extracted under reduced pressure. Since the hemolytic properties of different commercial saponins are variable (Hiller, Plazin, and van Slyke) it is recommended that saponin be replaced by an infusion of senega root or other substitutes. Lactic acid is added to liberate all of the CO_2 so that CO_2 and O_2 may be determined on a single sample. The partial pressure of the gas is measured in a mercury manometer calibrated in centimeters, after absorption of CO_2 (P_1), and of O_2 (P_2). Thus, partial pressure of O_2 is obtained ($P_3 = P_1 - P_2$) and its volume can be calculated at STPD (0°C, 760 mm Hg, dry). All reagents used must be free of physically dissolved gases in significant quantities.

If a significant amount of an anticoagulant (heparin) is used in drawing a blood sample, the O_2 content calculated from the above should be corrected using the following formula.

$$V_T = \frac{B_S \times V_U}{B_S - H}$$

where V_T = total O_2/100 ml blood, ml
B_S = volume of blood drawn up in syringe, ml
V_U = uncorrected volume O_2/100 ml blood,
H = volume of heparin used, ml

For example, if 0.2 ml of heparin is mixed with blood drawn to the 10-ml mark, and the uncorrected oxygen content is 20.0 ml/100 ml of blood,

TABLE 4-42. OXYGEN AND CARBON DIOXIDE CONTENT OF BLOOD

(in ml per 100 ml blood containing 15.4 Gm hemoglobin)

	Oxygen	Carbon dioxide
Venous blood		
Physically dissolved	0.1	3.0
Chemically combined with Hb	13–15	55.0
Total	15.1	58.0
Arterial blood:		
Physically dissolved	0.24	2.50
Chemically combined with Hb	19.65	45.50
Total	19.89	48.00
Arterial blood exposed to room air in tonometer:		
Physically dissolved at 25°C	0.62	
Maximum chemically combined with Hb	20.64	
Total	21.26	

the corrected O_2 content will be 20.41 ml/100 ml of blood.

$$\frac{10 \times 20}{10.0 - 0.2} = x = 20.41 \text{ ml/100 ml blood}$$

Oxygen Capacity and Arterial Oxygen Saturation. Oxygen capacity is the maximum ability of hemoglobin to combine with oxygen. According to Hufner each gram of hemoglobin maximally combines with 1.34 ml O_2. Oxygen capacity can be determined in a sample of blood by the *van Slyke-Neil method* after the sample, exposed to room air, has been rotated in a tonometer to convert any reduced hemoglobin (Hb) to oxyhemoglobin (HbO_2), or after equilibrating the blood directly in the van Slyke extraction chamber as recommended by Roughton et al. Arterial oxygen saturation may be expressed by the following formula:

$$O_2 \text{ saturation, per cent} = \frac{HbO_2}{Hb + HbO_2} = \frac{A_T - D_A}{Cap_T - D_{Cap}}$$

where A_T = total arterial O_2 content, ml/100 ml blood

D_A = O_2 dissolved in arterial blood, ml/100 ml blood

Cap_T = total O_2 capacity content of blood exposed to air at room temperature, ml/100 ml blood

D_{Cap} = O_2 dissolved in capacity blood, exposed to air at room temperature, ml/100 ml blood

Suppose the amount of O_2 dissolved in arterial blood is 0.24 ml/100 ml blood, and the amount of O_2 dissolved in capacity blood, exposed to room air at 25°C, is 0.62 ml/100 ml of blood. If total O_2 content of arterial blood is 19.89 ml/100 ml blood and that of blood exposed to room air is 21.26 ml/100 ml blood, the uncorrected arterial O_2 saturation is 93.5 ml/100 ml blood, while the corrected O_2 saturation is 95.1 ml/100 ml blood.

$$\frac{19.89}{21.26} = 93.5 \qquad \frac{19.89 - 0.24}{21.26 - 0.62} = 95.1$$

Besides the correction for physically dissolved O_2, other possible errors in the determination of O_2 capacity of blood are as follows:

1. The blood sample, collected from the rotated tonometer, usually contains a higher proportion of red blood cells to plasma than does the original blood analyzed for O_2 content. Thus, a correction should be made based upon the determinations of total hemoglobin or hematocrit of the red cells on the samples of blood tested for content and capacity.

2. Inactive hemoglobin and methemoglobin, which do not combine with oxygen (1.7 per cent in an average blood sample), may revert wholly, partly, or not at all to active hemoglobin during the rotation, so that the oxygen content of the blood, exposed to room temperature in air, is usually slightly higher by variable small amounts. Therefore, the value of arterial oxygen saturation is proportionately lower.

Techniques of Collecting Arterial Blood Anaerobically via Arterial Puncture. SELECTION OF NEEDLE. When only one sample of arterial blood is required, a sharp 1.5-in., 20-gage needle with a short concave bevel is preferred. For collecting serial samples of arterial blood, a Cournand arterial needle (1.5-in., 18-gage) is best, especially if multiple blood pressure measurements are also to be made. For collecting many samples of blood in a subject whose position must be changed (left heart catheterization using the prone position) a 1.5-in., 18-gage, thin-walled needle is preferred. After the needle is inserted into an artery, a polyethylene catheter, PE 50, is pushed through the needle bore and advanced into the lumen of the artery. The needle may then be withdrawn leaving the catheter in position for use. The needle point must be very sharp or else it may fail to penetrate the arterial wall.

PREPARATION OF SYRINGE. A 5- or 10-ml Luer-lock syringe is lubricated lightly and evenly with petroleum jelly (Vaseline) before autoclaving. Excess lubricant in the barrel or on the end of the plunger should be avoided because of the possibility that air bubbles might be entrapped; these would prevent anaerobic withdrawal of blood. A 20-gage, 1.5-in. needle is connected to the syringe and 1 ml of heparin (1,000 units/ml) is drawn into the barrel. The syringe is then pointed upward, its plunger is pulled to full capacity and then returned to the 1-ml mark. This maneuver wets the barrel with heparin and removes any air trapped in the space between the barrel and plunger. By changing the position of the syringe and slightly withdrawing and pushing the plunger, the remaining air bubbles can be expelled. Only 0.1 or 0.2 ml of heparin is allowed to remain in the syringe while the excess heparin is transferred to another syringe and the procedure is repeated time and again.

SELECTION OF ARTERIES. In adults and children beyond the age of 5, the brachial artery proximal to the antecubital fossa of either arm is preferable because it is relatively superficial, palpable, and adequate in size. The femoral artery just above the inguinal ligament is used in small children and

infants, as well as in adults in whom brachial arterial puncture has failed.

IDENTIFICATION OF THE COURSE OF THE BRACHIAL ARTERY. Palpation of the brachial artery by the left index finger alone, at or about *the site of needle* entry is not sufficient, because a slight deviation of the needle from the course of the artery may lead *to failure of entry*. First, at approximately 3 to 4 cm proximal to the proposed point of needle entry, the pulsation of the artery is carefully palpated with the left index finger. The left middle finger is now used to mark this upper point while the left index finger is moved downward *to slightly above the entry site*.

LOCAL ANESTHESIA. The skin is cleansed with a solution of Zephiran chloride in alcohol Infiltra*tion of the skin* with 0 5 to 1 per cent Novocain is performed by means of a 24-gage, 0 5-in needle and a 5-ml syringe. The subcutaneous and deeper tissues are also infiltrated with 1 per cent Novocain with the needle at an angle of 45° toward the course of the artery. This step should not be omitted, especially when the needle is to remain in the artery for long periods of time

ARTERIAL PUNCTURE The syringe with a 20-gage, 1 5-in. needle (containing 0 1 ml of heparin) is held in the right hand at an angle of 45° and the skin and subcutaneous tissue entered at the site of Novocain infiltration The needle is pushed forward at this angle toward the course of the artery, which is identified by the left middle and index

flow Once the needle is in the lumen of the artery, its position should not be altered until the desired quantity of blood is collected by gentle decompression of the plunger with the left hand In many instances, the needle may penetrate both sides of the arterial wall. In this case, needle and syringe should be withdrawn slowly until bright-red blood appears in the syringe. If only one blood sample is necessary, the needle is quickly withdrawn after sampling and a loose large gauze pad or sponge is quickly and forcefully applied over and above the site of needle entrance, 2 to 3 cm above the skin puncture Heavy pressure over the artery should be maintained for at least 5 min *If* blood or a hematoma appears at the puncture site upon release of the pressure, another 5 min of pressure are indicated If more time is necessary, a *firm bandage* is applied over the gauze or sponge with the pressure point over or about the *puncture site* (never below). The needle is then *disconnected from* the syringe and the latter is made airtight by closing it with a metal cap filled with mercury. The *blood inside* the syringe is mixed with the heparin solution (0.1 ml) by shaking the syringe for 1 to 2 min. Any air bubbles appearing around the heparin solution should be removed before connecting the metal cap to the syringe. Since the air bubbles usually contact the heparin solution only, the arterial blood being collected will not be affected.

In *multiple blood sample collection*, a Cournand arterial needle is inserted in the same manner, except that it is usually not connected to a syringe. When bright-red blood appears in the needle bore, the smaller inside needle is removed and a blunt stylet is inserted in the lumen. The angle of the needle should be changed to about 20° to 25° before the needle with the stylet is advanced along the course of the arterial lumen. The stylet is then removed to determine whether the needle is still in the artery, as revealed by a pulsating flow of arterial blood Blood samples may be collected at varying intervals as described for a single blood sample.

When an 18-gage, 1.5-in, thin-walled needle is used, and a polyethylene catheter, size PE 50, is to be introduced and left in the arterial lumen (as in left heart catheterization), the proximal end of the needle is held by the middle and index fingers and the stylet is pressed in place with the thumb. It is most important to alter the angle of the needle to 20° to 25° when arterial blood appears after temporary removal of the stylet. The needle with the stylet is then advanced approximately ¼ to ½ in (If the needle forms an angle of 45° with the artery, it is difficult to introduce the catheter, and the patient usually complains of sharp pain.) A polyethylene catheter is then introduced into the bore of the needle and advanced to the desired position as soon as the stylet is removed

The position of the polyethylene catheter is identified by injection of 1 ml of 75 per cent contrast medium (Urokon or Neo-iopax) into the catheter The needle is then withdrawn and the catheter is left in place A large sponge or loose gauze is applied with pressure to the site of catheter entry into the artery. Sustained pressure can be effectively maintained by adhesive tape or elastic bandage The catheter is now attached through a three-way stopcock to the sampling syringe and a bottle of heparinized saline placed at a level higher than the mean arterial pressure. This will maintain a continuous drip between sampling periods Because of lower clotting tendency, patency of the catheter can also be maintained by intermittent flushing every 10 or 15 min with heparinized saline solution. During sampling, the first 0 5 ml of blood should be discarded, that following should be collected in the usual manner

Technique of Collecting Arterialized Capillary Blood. The patient's hand is either wrapped in a hot towel or immersed in water at 45°C for 15 to 20 min. The middle or fourth finger is dried with gauze and cleansed with 70 per cent ethyl alcohol. A deep finger puncture, 4 mm long, is made with a knife blade held at an angle of 30°. Arterialized capillary blood will flow spontaneously and rapidly from the puncture. The blood is collected in a 2-ml, lubricated, and heparinized syringe by means of a small plastic funnel while an assistant withdraws the syringe plunger according to the rate of blood flow. According to Hultgren, the oxygen content of the arterialized capillary blood is almost identical with that obtained by arterial puncture If anaerobically arterialized capillary blood is preferred, the finger should be immersed in liquid paraffin, contained in the plastic funnel When collecting blood from newborn infants, a deep puncture, 4 mm long, is made along the side of the heel of a previously warmed foot.

If the ear is used, it is heated by radiant heat for 10 min at an air temperature of 45°C measured next to the ear lobe. The skin is cleansed with alcohol and punctured The arterialized capillary blood is caught in heparin or oxalate solution in a specially constructed funnel from which samples may be drawn with a micropipette

Technique of Collecting Arterialized Venous Blood. The hand is immersed in hot water at 45°C for 15 to 20 min. Arterialized venous blood is collected anaerobically from any convenient vein on the back of the hand Arterialized capillary blood is preferable in small children

MEASUREMENT OF OXYGEN SATURATION OF BLOOD WITH OXIMETERS

General Considerations. In man, the arterial oxygen saturation can be determined without taking blood from the artery in the form of arterialized blood as it circulates through a translucent part, e.g., pinna of the ear, or fold of the hand, by means of an ear oximeter A device of this type was first described by Matthes and others, and later developed by Millikan. A modified Millikan oximeter was described by Wood et al The last device can be used not only to measure the change in arterial oxygen saturation as does the original Millikan oximeter, but to measure the absolute value of the arterial oxygen saturation. The *channel oximeter* (Drabkin and Schmidt) was developed primarily for hemolyzed, undiluted blood, but the result for whole, unhemolyzed blood is less dependable. Wood et al. have made photometric readings on undiluted, nonhemolyzed human blood diverted into a cuvette made of polyethylene tubing. This device gives an immediate oxygen-saturation reading in blood samples drawn during diagnostic right heart catheterization.

Principle of Oximetry for O_2 Saturation. All oximetery is based upon the fact that oxyhemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) transmit almost identical infrared light but that oxyhemoglobin absorbs less visible red light (600 to 720 M/U) than reduced hemoglobin does. According to Beer's law of optical absorption, radiation traversing an absorbing solution of finite depth suffers a logarithmic reduction in its intensity. This law may be applied to the hemoglobin of the unlaked corpuscles of whole blood. The curve is not linear above 90 per cent O_2 saturation, especially between 95 to 100 per cent saturation.

The O_2 capacities determined by either ear or channel oximeters are not as accurate as the van Slyke-Neil gasometric method. In ear oximetry, venous blood may still be present and thus lower the arterial saturation. The *histamine ear-flush method* may eliminate this error Each phototube has its own spectral response characteristics and should be calibrated against the known arterial saturation obtained by the van Slyke-Neil method. A phototube, which has been calibrated and has given a satisfactory response for several months, may suddenly become "fatigued" It should be discarded and a new one must be calibrated and substituted for it.

The arterial or venous oxygen content is calculated from known hemoglobin values and oxygen saturation of the blood, as determined by the oximeter The Millikan ear oximeter as modified by Wood et al, as well as the channel oximeter, give absolute values of oxygen saturation Wood claimed that in the oxygen-saturation range of 13 to 100 per cent, the difference between simultaneous van Slyke and photoelectric values was less than 5 per cent saturation in 97 per cent of the determinations. Also, a single measurement of oxygen saturation made by the channel oximeter falls within 3.6 per cent saturation of that obtained by van Slyke's analysis This excellent result is obtained only under special laboratory conditions and is not easily duplicated in other laboratories.

PATTERNS OF PRESSURE

NORMAL PATTERNS OF PRESSURE IN THE CARDIAC CHAMBERS AND LARGE VESSELS

Considering that the patterns of the two venae cavae largely reflect the waves of the right atrium (with some degree of distortion), the description should start from the latter.

Right Atrium. The right atrial pattern is basically formed by two positive waves, one in presystole (preceding ventricular systole) and the other during early ventricular diastole (Fig 4-174)

PRESYSTOLIC WAVE. The presystolic wave, to be called A wave, is caused by the contraction of the right atrium It starts about 0.14 to 0 15 sec before the beginning of the 1st sound in adolescents and adults, and between 0 12 and 0.14 sec in children Its peak always precedes the onset of the 1st sound, the latter usually starting during the last part of the descending branch of the A wave The peak of the A wave always precedes the R wave of the electrocardiogram A similar relationship can be observed in the dog If the phonocardiogram of the subject has a 4th (atrial) sound, this is practically simultaneous with the peak of the A wave

wave of the pressure tracing (increase of pressure) Both are an expression of the atrial contraction

SYSTOLIC EVENTS At the beginning of ventricular systole, a small notch in the pressure tracing reveals the closure of the tricuspid valve. Instead of a notch, there may be only a slower drop of the pressure curve, or even a second (small) peak during the 1st sound We suggest that this notch or peak be represented by the symbol AV (atrioventricular) since the letter C, frequently employed by others, was originally used to describe the C wave of the venous tracing (C stands for carotid, according to the description of McKenzie). In regard to the electrocardiogram, the AV notch falls during the R-S segment of the ventricular complex, or at the peak of the S wave

Another small, positive, wave may occur later, after the end of the 1st sound (or during the end of that sound, if it is abnormally prolonged). This systolic notch is simultaneous with the rise in pressure of the aorta and is probably due to vibration of the right atrial wall caused by the ascending aorta This notch, which can be called C, is far from being a constant finding

Most of the ejection phase is accompanied by a decrease in pressure (Fig. 4-174) which is due to the lowering of the AV floor and the tricuspid valve as a result of the powerful pull of the ventricular septum, the right ventricular wall, and the papillary muscles It should be called the *systolic collapse*.

DIASTOLIC WAVE. The ascending branch of the *systolic collapse* rises gently during the last part of ejection because of venous flow into the atrium. A new peak is reached from 0 04 to 0 07 sec after the main vibration of the 2d sound, at the time of the opening of the tricuspid valve (Fig 4-174). It is apparent that this opening causes a sudden change in pressure in the atrium by "removing the bottom" of the chamber. This peak is called the V wave The peak of the V wave is usually lower than that of the A wave but may be equal to it, and is never higher in normal individuals The V-wave peak follows the end of the T wave of the ECG.

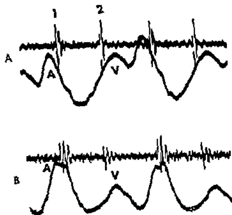


Fig 4-174 Patterns of pressure of the right atrium in normal subjects, phonocardiograms for timing. A Five-year-old child. B A 22-year-old girl

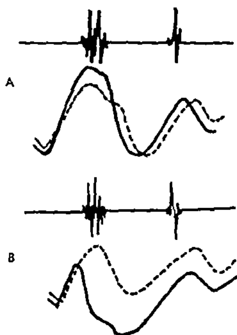


Fig. 4-175. Relationship of caval to atrial pressure in normal subject A. Continuous line, RA; stippled line, SVC. B. Continuous line, RA, stippled line, IVC.

Superior Vena Cava. The pressure tracing of the superior vena cava is similar to that of the right atrium Superimposed tracings, however, show certain differences between the right atrium and the cavae (Fig 4-175).

1. A slight delay of the A and V waves due to the time necessary for their transmission from the atrium to the vena cava.
2. A prominent C wave, which is probably due to a systolic impact of the ascending aorta on the vena cava.
3. The possible absence of a separate notch for the AV wave.

Inferior Vena Cava. The pressure tracing of the inferior vena cava is quite similar to that of the superior vena cava However, the peak of the A wave is frequently more delayed than in the latter so that it may fall at the beginning of the 1st sound. Notches AV and C may be completely absent at the beginning of systole. The delay between right atrial and inferior caval waves is greater than in the case of the superior vena cava (Fig 4-175)

Left Atrium. The left atrium of the dog is easily entered by retrograde arterial catheterization. In man, direct puncture through the back is a safer procedure which has been used routinely by the authors.

The pressure tracing of the dog shows a rapid, often diphasic, presystolic wave (A wave) starting about 0.06 sec before the beginning of the 1st sound, a tall notch during the 1st sound (it should be called AV), a deep systolic collapse, and a high V wave. The relationship between left atrial and left ventricular pressure is apparent in Fig. 4-176

Left atrial patterns of human beings have been recorded in cases of atrial septal defect (or anomalous venous drainage) by Cournand et al. and by Nahas et al. Direct puncture after thoracotomy allowed Wynn et al. to study these pulses in normal subjects. Later on, Facquet et al, Allison and Linden, and Epps and Adler studied the left atrial pulse by transbronchial puncture, while Bjork and Kent et al studied it by transthoracic puncture. In the authors' collection, five subjects presented perfectly normal data and their tracings can be accepted as normal.

Left atrial tracings are grossly similar to those of the right atrium (Fig 4-177).

PRESYSTOLE The presystolic rise of pressure is well developed and ends before the 1st sound. It is followed by the AV wave. The latter is a separate wave and may be diphasic or triphasic. It usually has a sudden drop, much more rapid than that observed in the right heart. (A similar drop is noticed in tracings recorded in dogs.)

SYSTOLE During systole, the left atrium shows a *systolic collapse* similar to that observed in the right atrium and due to the same causes. The systolic collapse is terminated by



Fig 4-176. Simultaneous left atrial and left ventricular pulses recorded in a normal dog, using same amplification and base line. A Phonocardiogram, B. Pressure pulses C Electrocardiogram.

a gentle rise which lasts through the 2d sound and terminates with the V wave

DIASTOLE. The V wave occurs in early diastole, from 0 05 to 0 08 sec after the main vibration of the 2d aortic sound It is always lower than the A wave in normal subjects Following this wave, there is a second gentle depression, the *diastolic collapse*, which is followed by a rise of pressure during diastasis ending with the following A wave

Ventricles. Ventricular pressure tracings of animals have been recorded for a century The plateau-like pulse described by Chauveau and Marey in the horse was also recorded later in the dog. However, the shorter duration of systole in the dog frequently caused this pulse to have a more rounded contour.

According to a classic description (Wiggers) the typical human tracing rises during the tension period (first part of 1st sound), reaches its maximum level at, or soon after, the end of the 1st sound, remains level or gently slopes down during systole, then starts to drop rapidly at the beginning of protodiastole (shortly before the 2d sound) The lowest level is reached some time after the 2d sound and at the time that the AV valves begin to open After this, rapid filling begins and there is a short phase of rapid rise, which is soon followed by an even course Certain variations may occur but are not remarkable.

In order to exclude the different contours possibly arising from using a method different from that employed in man, the authors have catheterized dogs by using a method which is identical to that currently used for right or left heart catheterization in man

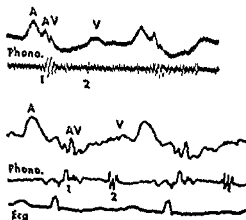


Fig. 4-177. Left atrial pressure pulses in normal adults.

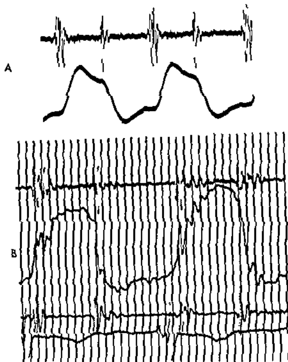


Fig 4-178. Right ventricular pressure pulses in normal subjects. A Five-year-old girl. B A 30-year-old man.

RIGHT VENTRICLE Some tracings are similar to the classic tracings recorded with older types of manometers Others, recorded with a high-sensitivity microphone and an electromanometer, show two rapid complexes, one at the beginning and the other at the end of the 1st sound It is apparent that these are caused by the rapid swings of the valves; first the closure of the tricuspid valve, then the opening of the pulmonic valve. These complexes are usually not recorded because of the slower response of the manometer and the lower amplification (this is particularly true in the case of the left ventricle) A conic peak in systole is definitely atypical and often due to artifacts.

Right ventricular tracings are presented in Fig 4-178 They show a diastolic pressure which is at or near zero Some tracings show minor abnormalities including slow rise and drop or a conical shape It is likely that minor artifacts, not sufficient to alter the levels of pressure, were involved. It is important to note that, while the top of the plateau-like pulse

of the normal ventricle may present different variations, it never shows a progressive rise or a double rise (after the ascending slope), as do some of the tracings of ventricles from clinical cases.

LEFT VENTRICLE. The tracing of the left ventricle of the dog is similar to that of the right There is a rectangular, plateau-like wave during the entire systole. Lower amplification is necessary because of the higher pressure. Therefore, the small details of the tracing originating in valvular events are poorly visible or absent The drop in pressure which takes place shortly before the 2d sound appears as a steep decline with an end point at or near zero. Early diastole is accompanied by a rapid rise of short duration (rapid inflow), next, a gentle slope or a steady course is visible in diastole. The highest level of diastolic pressure is identical to the filling pressure of the left atrium.

In man, the tracing is basically the same (Fig 4-179). The presystolic rise is usually minimal (small amplification) Sometimes there is a small dip followed by a rise in early diastole. However, the tracing may not show this accident too clearly Small vibrations may be apparent during the ejection phase.

The Aorta and Brachial and Femoral Arteries. Arterial tracings, recorded in animals for a long time, have been registered in man only in the last few years. The aortic tracing is frequently studied by retrograde arterial catheterization. The normal aortic tracing shows the changes of contour which are typical of the central pulse. the anacrotic depression, the peak, the incisura, and the dicrotic wave (Fig. 4-180) Additional waves preceding the rise of the pulse have been explained

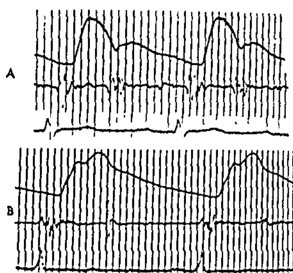


Fig. 4-180. Normal aortic tracings obtained through retrograde catheterization of two adults. The tracings are superimposed over phonocardiograms and electrocardiograms. A. Pattern of peripheral pulse (the tip of the polyethylene catheter was in the descending aorta) B. Pattern of central pulse (tip of the catheter near the aortic valve)

as an expression of presystolic atrial contraction causing a vibration of the aortic valve, and of an early-systolic bulging of the aortic leaflets during the tension period.

The brachial and femoral pulses, on the other hand, have the smoother contour characteristic of the peripheral pulse and show no evidence of an anacrotic depression

Pulmonary Artery. This tracing is typical of an arterial pulse with a pattern resembling that

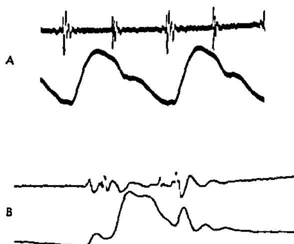


Fig. 4-181. Normal tracings of the pulmonary artery. A. Girl, 5 years of age. B Man, 30 years of age (B) shows transmission of a wave in early systole due to ventricular tension; the dicrotic wave is somewhat exaggerated.



Fig. 4-179. Normal tracing of the left ventricle in a woman 27 years of age.

of a peripheral pulse (Fig. 4-181). The reason lies in the marked distensibility of the pulmonary artery. The anacrotic notch is usually not visible, the peak is rounded and falls at about one-half of the ejection period, the incisura is deep and rounded and is followed by a high dicrotic wave.

In some tracings, a high, squarish wave (or several slow vibrations) can be observed in diastole. These should be considered artifacts, due to flopping of the catheter after the 2d sound and the effect of atrial and ventricular movements upon it. Careful withdrawal and reinsertion of the catheter may cause the disappearance of these spurious waves.

Pulmonary Branches. The pattern of pressure pulses in large branches of the pulmonary artery is similar to that of the main artery, and may be identical with it.

Pulmonary Artery Wedge Tracing (So-called Pulmonary Venous Tracing or Pulmonary Capillary Tracing). This tracing is far more variable than any other because of the following technical difficulties.

1. Possible transmission of pulmonary arterial pulses around the tip of the wedged catheter.

2. Possible rapid transmission of left atrial pulses through open arteriovenous thoroughfares.

3. Slow transmission of left atrial pulses through the minute capillary vessels of the lungs.

4. Vibration of the catheter due to movements of the heart (through which it passes) and of the lung (to which it is fixed).

This explains the variability of pattern, not only from patient to patient, but even in the same subject, if the catheter is withdrawn slightly and then wedged again.

The recording of "wedge" pressure was described by Hellems et al. (1948). They correctly attributed the mean pressure recorded by this technique to transmission of left atrial pressure. However, they recognized that multiple artifacts frequently render the readings incorrect. The pressure pulses have been recorded by firmly wedging the catheter into a small pulmonary arterial branch until it occluded the lumen, these were studied and described as being similar to those of the left atrium (Hellems et al., Lagerloef and Werkoe, Soulié et al.).

It has been stated that, because of slow transmission of the waves from the left atrium to the pulmonary arterioles, the waves of the "wedge" arterial tracing are similar to those of the left atrium but delayed in time. If this were so, a delay of not less than 0.05 sec should be observed, and there should be a fixed shifting of both the A and the V waves, the former would fall during or after the 1st sound (early systole) and the latter after about one-third of diastole or even at mid-diastole. Actually, as will be shown later, only the A wave has a major shift, when it is present. Later, it was suggested that a rapid transmission of pulse could occur through arteriovenous anastomoses. If this be true, it explains why the typical waves are not always present, closing of the arteriovenous thoroughfares would prevent any rapid transmission of waves and cause a general damping by the capillary bed. Only "mean" pressure would then be reliably recorded.

The authors have recorded pulmonary artery "wedge" tracings in normal dogs, in 8 normal human subjects, and in clinical patients in whom the pulses should not have been affected by their disease (small atrial septal defect, arterial hypertension, or moderate pulmonary fibrosis). They have been impressed by the following findings.

1. The pattern is extremely variable and frequently consists of several small waves in systole and diastole.

2. There may be only minimal oscillations of pressure.

3. Certain subjects present a pattern resembling that described by Soulié et al.

When the tracing is typical, the following details can be observed. At the time of the 1st sound there is a diphasic oscillation, usually of the positive-negative type (Fig. 4-182), which may be replaced by a monophasic, sharp peak. This notch is probably caused by a vibration of the catheter due to the double valvular movement which takes place at that time in the right heart. Therefore, it is the equivalent of the 1st sound. Following this vibration, there is a slow and smaller wave which takes place in early systole. This has been marked A because it is probably caused by a delayed transmission of the left atrial A wave. This is proved by the fact that the wave takes place earlier in patients with a prolonged conduction time and is absent in those with atrial fibrillation. During the remaining portion of systole, either a systolic

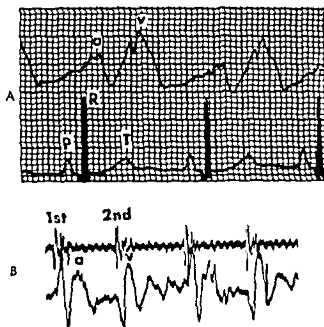


Fig. 4-182. Pulmonary wedge pressure pulses. A. Direct-writing apparatus, electrocardiogram. B. Photographic recording, high frequency gage; the upper tracing is a phonocardiogram

collapse or a straight line occurs. With the 2d sound, there is a vibration which is usually of the negative-positive type, this is immediately followed by a tall, positive wave coinciding with the opening of the mitral valve and which should be called the *V wave*

It is interesting to note that, while the "presystolic" wave shows a marked delay over the atrial contraction, the early-diastolic wave has only a minimal delay over the opening of the valve. This can be explained by the fact that atrial contraction is weak and causes a wave which moves backwards toward the capillary vessels of the lungs, while the opening of the AV valve causes a sudden forward movement of a long column of blood, from the capillaries to the left atrium

Whenever a recognizable pattern is recorded, this may be studied and interpreted, otherwise, no such study can be made The most undesirable possibility is that of recording a pulse transmitted from the pulmonary artery, whenever this happens, it can be confused with a retrograde systolic wave due to mitral regurgitation.

Pulmonary Vein Wedge Tracings (So-called Pulmonary Arterial Capillary Tracings). These tracings can be recorded by left atrial catheterization performed either through the bronchus or the chest wall, followed by firmly wedging the catheter into a pulmonary vein. A similar tracing can be obtained by right heart catheterization if the catheter passes into the left atrium through an atrial septal defect. The observed pattern is that of an arterial pulsation (Gensini et al.).

Coronary Sinus Tracing. The technique of catheterization of the coronary sinus was developed by Banfield et al. and was studied by Bing et al. The patterns of the pressure pulses recorded by wedging the catheter in the coronary sinus, or by having it in the same vessel without obstructing the flow, were studied by Read et al. They described a venous type of tracing (if the tip is not obstructing the flow) with no evident C wave and a higher pressure than that of the right atrium They also described a "ventricular" pattern (if the catheter is obstructing the flow by occluding the opening).

In one subject, a child of 5, subsequently recognized as normal, the authors recorded the coronary sinus pattern with the catheter wedged in the vessel (Fig. 4-183). The tracing had the following characteristics: a drop in pressure in late presystole and early systole; a sharp rise in pressure during early systole, and a plateau continuing through the rest of systole plus most of diastole.

No other known tracing has a similar pattern. The form of this tracing may be explained by the systolic squeezing of the capillaries of the ventricular wall plus the well-known diastolic flow through the capillary bed.

ABNORMAL PATTERNS

The following abnormal patterns are the most significant.

Venae Cavae and Right Atrium. The abnormal pattern coincides with increased right atrial and venous pressure A special pattern is typical of tricuspid insufficiency

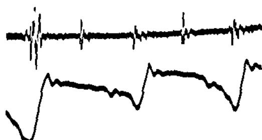


Fig. 4-183. Tracing obtained by wedging the catheter in the coronary sinus of a normal 5-year-old girl.

Right Ventricle. The abnormal pattern indicates right ventricular strain.

Pulmonary Artery. An abnormal pattern is typical of pulmonic stenosis.

Pulmonary Wedge Tracing. An abnormal pattern in this tracing is typical of mitral insufficiency.

Left Atrium. The most important is a pattern typical of mitral insufficiency; abnormal patterns are also present in certain cases of mitral stenosis. Another abnormal pattern is typical of mitral insufficiency plus stenosis.

Left Ventricle. The abnormal pattern indicates left ventricular strain

Aorta. There are abnormal patterns typical of aortic stenosis and of aortic insufficiency.

FORMULAS USED IN CARDIAC CATHETERIZATION

The calculation of resistance in the pulmonary circulation and of the size of valvular openings presents great interest.

By the application of *Poiseuille's equation*·

$$\text{Resistance} = \frac{\text{pressure gradient}}{\text{rate of flow}}$$

several formulas concerning cardiovascular resistances have been derived for the evaluation of some of the unknown dynamic facts of intracardiac and pulmonary circulations The Poiseuille equation is based on a rigid tube system with continuous flow of homogeneous fluid. However, the cardiovascular system has a pulsatile flow and elastic arterial walls Therefore, only approximate data can be obtained from these formulas.

RESISTANCE TO BLOOD FLOW

Pulmonary Arteriolar, Total Pulmonary, and Mitral Resistances. It has been suggested that the pulmonary arteriolar resistance, or pulmonary vascular resistance proximal to the capillary bed, can be evaluated by Eq (1).[16]

$$PAR = \frac{(M_{pa} - M_{pc}) \times 1{,}332}{CO} \quad \text{dyne-sec-cm}^{-5} \quad (1)$$

where PAR = pulmonary arteriolar resistance
M_{pa} = mean pressure of pulmonary artery
M_{pc} = mean pulmonary "capillary pressure" (or, better, mean pulmonary arterial wedge pressure)
CO = cardiac output, ml/sec
1,332 = factor for converting mm Hg to dynes/cm²

The *total pulmonary resistance* (TPR) can be evaluated by Eq (2)

$$TPR = \frac{M_{pa} \times 1{,}332}{CO} \quad \text{dyne-sec-cm}^{-5} \quad (2)$$

where TPR = total pulmonary resistance and the other symbols are as in Eq. (1).

[16] Cardiac index can be substituted for cardiac output, and the unit will be dyne-sec-cm⁻⁵/m² of body surface.

It has been further suggested that the *resistance of the mitral valve* (MVR) can be evaluated from the difference between Eqs (1) and (2). Subtracting, one obtains Eq. (3).

$$MVR = \frac{M_{pc} \times 1{,}332}{CO} \quad \text{dyne-sec-cm}^{-5} \quad (3)$$

It is apparent that evaluation of mitral resistance is based entirely on the data for M_{pc} (or the mean values of pulmonary arterial wedge pressure). The validity of the formula is based on the assumption that the end-diastolic pressure of the left ventricle is zero, a point which is questionable, especially in patients with mitral valve disease.

Gorlin et al assumed a pressure of 5 mm Hg as a normal value for the diastolic level of the left ventricle The possible existence of unknown elements, i e, mitral insufficiency, left ventricular failure, myocardial fibroelastosis of the left ventricle, or constrictive pericarditis, may further invalidate these calculations On the other hand, if the left atrial pressure and left ventricular diastolic pressure are obtained by means of left heart catheterization, these possibilities can usually be ruled out.

It is also apparent that the blood flow through the mitral valve was computed as though it occurred throughout the entire cardiac cycle. Actually, the blood flow through this valve takes place only during diastole. The correct rate of flow (ml/sec) is obtained by multiplying CO by the quotient of the total duration of cardiac cycles (measured) (T_c), divided by the duration of diastole of same cardiac cycles (measured) T_d.

The duration of diastole can be obtained from measurements of either heart sounds or left atrial pressure tracings. In heart-sound tracings the duration of diastolic flow is measured from the opening snap of the mitral valve to the beginning of the 1st heart sound When an opening snap is not present, the duration of the interval between the beginning of the 2d sound and the beginning of the 1st sound (minus 0.06 to 0.08 sec) may be used In left atrial pressure tracings, the duration of diastolic flow is measured from the V wave (opening of the mitral valve) to the following AV wave (closure of the mitral valve) It is also

necessary to measure several cardiac cycles during one or two respiratory cycles, especially in patients with atrial fibrillation.

The mitral valvular resistance can be better evaluated through the use of Eq. (4) and the value obtained is usually confirmed by subsequent evidence.

$$MVR = \frac{(D_{la} - D_{lv})\,1{,}332}{CO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (4)$$

where D_{la} = mean diastolic pressure of left atrium
D_{lv} = mean diastolic pressure of left ventricle
T_c = duration of total cardiac cycles (measured)
T_d = duration of diastole of same cardiac cycles (measured)

The authors have found that the incidence of pure mitral stenosis is much rarer than that of mitral stenosis with minimal to moderate mitral insufficiency In the latter, the blood flow through the mitral valve during diastole should be greater than the calculated effective aortic forward flow which assumes no mitral insufficiency. Therefore, the MVR calculated by use of Eq. (4) is greater than it should be, and *actual mitral valve resistance is less.*

Further deductions from data of catheterization were drawn in order to evaluate the *elasticity resistance of the pulmonary vessels* This would be deduced from the data of pulse pressure and flow (cardiac output). The term "elasticity resistance," apparently meaning the reciprocal of distensibility, is then compared to *resistance to flow* for both the pulmonary and the systemic circuits The ratio of elasticity resistance to flow resistance was found to be 3 5 for the pulmonary circulation and 1.2 for the systemic circulation These data have been criticized and cannot be accepted without further proof.

Resistance of Other Stenotic Valves. AORTIC STENOSIS. The total resistance of the stenotic aortic opening can be calculated by using Eq (5)

$$AVR = \frac{(S_{lv} - S_{ba})\,1{,}332}{SO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (5)$$

where AVR = total resistance to blood flow through the stenotic aortic valve
S_{lv} = left ventricular mean systolic pressure, mm Hg
S_{ba} = aortic or brachial arterial mean systolic pressure, mm Hg
SO = systemic blood flow, ml/sec
T_c = duration of total cardiac cycles (measured)
T_d = duration of diastole of same cardiac cycles (measured)

The duration of systole is measured from the beginning of the upstroke of the aortic pressure tracing to the dicrotic notch, or from the last major vibration of the 1st sound to the 2d aortic sound in heart-sound tracings. Since a systolic murmur may fuse with one or both heart sounds, the second method may be unsuitable.

Equation (5) gives more reliable data than another formula which had been previously suggested; in that one the flow of blood through the aortic valve was treated as though it occurred throughout the entire cardiac cycle. Actually, the flow of blood through the stenotic aortic valve takes place only during the phase of systolic ejection.

TRICUSPID STENOSIS. By substituting right atrial mean diastolic pressure (D_{ra}) for the corresponding left atrial data (D_{la}) in Eq. (4), and right ventricular mean diastolic pressure (D_{rv}) for the corresponding left ventricular data (D_{lv}) in Eq (4), the resistance of the tricuspid valve (TVR) can be deduced by means of Eq. (6):

$$TVR = \frac{(D_{ra} - D_{rv}) \times 1{,}332}{CO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (6)$$

PULMONIC STENOSIS. The total resistance of the pulmonic opening can be calculated by using Eq. (7) irrespective of whether there is valvular, infundibular, or a complex type of stenosis.

$$PVR = \frac{(S_{rv} - S_{pa}) \times 1{,}332}{PO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (7)$$

where PVR = total resistance to blood flow through the stenotic pulmonic valve
S_{rv} = right ventricular mean systolic pressure, mm Hg
S_{pa} = pulmonary arterial mean systolic pressure, mm Hg
PO = pulmonary blood flow, ml/sec

The resistance of the infundibulum (PIR) in a complex type of stenosis can be calculated by using Eq (8)

$$PIR = \frac{(S_{rv} - S_i) \times 1{,}332}{PO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (8)$$

where S_i = infundibular mean systolic pressure, mm Hg

Likewise, the resistance of the stenotic pulmonary valve (RPV) in a complex type of stenosis can be obtained by means of Eq. (9)

$$RPV = \frac{(S_i - S_{pa})\,1{,}332}{PO(T_c/T_d)} \quad \text{dyne-sec-cm}^{-5} \quad (9)$$

The *calculated peripheral resistance* (PR) can be obtained by using Eq. (10):

$$PR = \frac{M_{ba} \times 1{,}332}{CO} \quad \text{dyne-sec-cm}^{-5} \quad (10)$$

where M_{ba} = mean brachial arterial pressure, mm Hg

Formulas for calculating valvular area are derived by the application of the two well-known hydraulic equations (*a*) and (*b*).

$$C_b = k_o O C_V \qquad (a)$$

where C_b = changes in rate of flow through orifice
k_o = coefficient of orifice contraction
O = fixed orifice
C_V = changes in velocity

$$C_V^2 = k_V^2 2gh \quad \text{or} \quad C_V = k_V\sqrt{2gh} \qquad (b)$$

where h = pressure gradient, mm Hg
g = gravitational acceleration, 980 cm/sec/sec
k_V = coefficient of velocity (only a certain fraction of pressure is converted to velocity)

Combining Eqs (a) and (b) gives a formula for area (A), Eq (c)

$$A = \frac{F}{K \times k_V\sqrt{2gh}} = \frac{F}{K \times 44.5\sqrt{P_1 - P_2}} \quad \text{cm}^2 \qquad (c)$$

where F = rate of flow through orifice
K = discharge coefficient (empirical constant)
$44.5 = \sqrt{2g} = \sqrt{1960}$
$h = P_1 - P_2$, pressure gradient across orifice

Mitral Valve Area An attempt to measure mitral valve area (A_{mv}) was made by Gorlin and Dexter through a modification of hydraulic formula (c) which gives Eq. (11)

$$A_{mv} = \frac{F_{mv}}{31\sqrt{PC - 5}} = \frac{F_{mv}}{31\sqrt{D_{la} - D_{lv}}} \qquad (11)$$

where F_{mv} = mitral valvular rate of flow, ml/sec
D_{la} = mean diastolic pressure, left atrium
D_{lv} = mean diastolic pressure, left ventricle

In mitral stenosis the discharge coefficient K [formula (c)] determined before left ventricular diastolic pressure was available, is 0.7, which may have to be changed Thus

$$K\sqrt{2g} = 0.7 \times 44.5 = 31$$

F_{mv} is calculated by using the formula below

$$F_{mv} = \frac{CO}{\Sigma_d}$$

where CO = cardiac output, ml/min
Σ_d = summation of diastolic period, sec/min (obtained by multiplying measured diastolic filling per beat by heart rate per minute)

Where atrial fibrillation exists, Σ_d can be calculated by the following formula.

$$\Sigma_d = \frac{T_d}{T_c} \times 60$$

where T_d = duration of diastolic periods of same cardiac cycles (measured), sec
T_c = duration of total cardiac cycles (measured), sec

Simultaneous pressure tracings of the left ventricle and atrium showed that the filling of the left ventricle through a stenotic mitral valve may last through the early part of the ventricular tension period Therefore, duration of diastolic filling can be measured accurately only by means of phonocardiography or left heart catheterization.

The numeral 31 used in Eq (11) is a constant which is supposed to correct for anomalies of discharge through the orifice and errors in calculating the diastolic filling period, and to convert pressure from mm Hg to cm H_2O. The numeral 5 used in Eq. (11) is an acceptable estimated level of left ventricular mean diastolic pressure.

Aortic Valve Area. The cross-sectional area of the aortic valve (A_{av}) is calculated by Eq (12) (after Gorlin)

$$A_{av} = \frac{F_{av}}{C \times 44.5\sqrt{S_{lv} - S_{ba}}} \quad \text{cm}^2 \qquad (12)$$

where F_{av} = aortic valve flow, ml/sec
S_{lv} = mean left ventricular systolic pressure, mm Hg
S_{ba} = brachial arterial mean systolic pressure, mm Hg
C = empirical constant, to be derived

$$F_{av} = \frac{CO}{E_s}$$

where CO = cardiac output, ml/min
E_s = systolic ejection period, sec/min

$$E_s = \frac{T_s}{T_c} \times 60$$

where T_s = total duration of systolic ejection periods of cardiac cycles (measured), sec
T_c = total duration of some cardiac cycles (measured), sec

A single systolic ejection period can be measured on the aortic and left ventricular pressure tracings from the point where the beginning of the aortic upstroke (or where left ventricular pressure equals arterial diastolic pressure) to the point of the aortic incisura, or that where left ventricular pressure falls below the arterial dicrotic notch.

The value of the empirical constant C has not yet been derived because left heart catheterization has been in use for only a few years Patients studied by the authors have not been subjected to either direct-vision valvotomy or autopsy for the purpose of measuring the aortic valvular cross-sectional area. At present, an arbitrary value of

1.0 is used for C. The figure may be too high because a conversion factor of 1.17 is included in C and the actual discharge coefficient $(C_v \times C_c)$ of the orifice may be lower than 0.85.

Pulmonic Valve Area. The cross-sectional area of the pulmonic valve (A_{pv}) is calculated by Eq. (13) (after Gorlin).

$$A_{pv} = \frac{F_{pv}}{C \times 44.5\sqrt{S_{rv} - S_{pa}}} \quad cm^2 \qquad (13)$$

where F_{pv} = pulmonic valve flow, ml/sec
S_{rv} = mean right ventricular systolic ejection pressure, mm Hg
S_{pa} = mean pulmonary arterial systolic pressure, mm Hg

$$F_{pv} = \frac{CO}{E_s}$$

A single systolic ejection period can be measured on the right ventricular pressure tracing from the point where right ventricular pressure equals pulmonary pressure to the point where right ventricular pressure crosses the pulmonary arterial dicrotic notch.

The measurement of mean pulmonary arterial systolic pressure should be carefully made because multiple artifacts are usually present in the pulmonary arterial pressure tracing. One should not consider the early diastolic rebound as the systolic pressure.

Tricuspid Valve Area. The cross-sectional area of the tricuspid valve (A_{tv}) is calculated by formula (14), a modification of Gorlin's formula

$$A_{tv} = \frac{F_{tv}}{C \times 44.5\sqrt{D_{ra} - D_{rv}}} \quad cm^2 \qquad (14)$$

where F_{tv} = tricuspid valve flow, ml/sec
D_{ra} = mean right atrial diastolic pressure, mm Hg
D_{rv} = mean right ventricular diastolic pressure, mm Hg

$$F_{tv} = \frac{CO}{f_d}$$

where f_d = diastolic filling period of the right ventricle, sec/min

The value of the empirical constant C in this formula has not yet been determined. Since no correction for diastolic filling is necessary, C is greater than 0.7. Assuming the discharge coefficient $(C_c \times C_v)$ to be 0.85, the value 1.0 was used by the Gorlins. This value for C may be changed with future collection of autopsy data.

Those interested in the formulas for calculating the diameter of a patent ductus arteriosus, or the areas of interatrial or interventricular septal defects, should consult a publication by the Gorlins.

WORK PERFORMED BY THE VENTRICLES

The work performed by the right ventricle (RVWD) can be calculated by formulas (15) or (15a), which are simple and practical. Formula (16) is based on the metric system and is more accurate.

$$RVWD = CO(S_{pa} - M_{ra}) \times 1{,}332 \quad \text{dyne-cm/sec} \qquad (15)$$

where CO * = cardiac output, ml/sec
S_{pa} = pulmonary arterial mean systolic pressure, mm Hg
M_{ra} = right atrial mean pressure (may be omitted in order to obtain an approximate value)
1,332 = factor to convert mm Hg to dyne/cm²

Since

1 erg = 1 dyne-cm and 1 joule = 10^7 ergs

by substituting joules and omitting M_{ra}, the formula may be simplified as follows.

$$RVWD = \frac{CO \times S_{pa} \times 1{,}332}{10^7} \quad \text{joules/sec} \qquad (15a)$$

A more accurate formulation would be

$$RVWD = \frac{(CI \times 1.055)[(S_{pa} - M_{ra}) \times 13.6]}{1{,}000} \quad \text{kg-m/min/m}^2 \qquad (16)$$

kg-m (meter)/min/m² (square meters of body surface)

where CI * = cardiac index in liters/min/m²
1.055 = specific gravity of blood
13.6 = specific weight of mercury

It can be further simplified by omitting M_{ra}:

$$RVWD = \frac{(CI \times 1.055)S_{pa} \times 13.6}{1{,}000} \quad \text{kg-m/min/m}^2 \qquad (16a)$$

By substituting brachial or femoral arterial mean systolic pressure (S_{ba}) for S_{pa}, and M_{la} for M_{ra}, the work done by the left ventricle (LV) can also be evaluated.

The calculation of the amount of blood flowing through shunts requires knowledge of several data including oxygen consumption by the patient and the oxygen contents and pressures of the various cardiovascular chambers and of the peripheral blood. For this reason, even though this study was particularly concerned with the pressures and pulses of the various chambers, the following pages

* Cardiac output = pulmonary output and cardiac index = pulmonary index in the absence of shunts.

will refer to oxygen-determination data. Thus most of the formulas needed in cardiac catheterization will be included in this single, brief chapter.

INTRACARDIAC SHUNTS

The evaluation of intracardiac shunts was attempted soon after right heart catheterization was introduced as a diagnostic procedure. Much of the following information is universally accepted

1. The oxygen contents of the superior and inferior venae cavae usually differ by 1 to 3 vol/100 ml. The blood sample of the inferior vena cava should be taken when the tip of the catheter is just below the diaphragm If this tip advances to the orifices of the hepatic veins (which usually carry blood with a lower oxygen content) while the sample is collected, then the oxygen content of the sample will be lower than it should (hepatic blood instead of mixed lower caval blood). If the tip is below the orifices of the hepatic veins, then the oxygen content of the sample is higher

2 The inferior vena cava carries about 55 to 60 per cent of the total amount of blood into the right atrium while the superior vena cava carries 40 to 45 per cent

will be mixed in the lower part of the right atrium and, more thoroughly, in the right ventricle

4 "Mixed venous blood" is more thoroughly mixed in the pulmonary artery than in the right atrium or ventricle of patients having no evidence of shunt

5 The following data are considered by the authors to be evidence of left-to-right shunt between the atria

a The average oxygen content of the right atrium should be at least 1 5 vol/100 ml higher than the average of the blood samples of the two venae cavae

b The oxygen content of a single right atrial blood sample should be at least 3 vol/100 ml higher than the average of the blood samples of the two venae cavae

c The oxygen content of 2 or more right atrial blood samples should be at least 4 vol/100 ml higher than that of either caval sample

6 In the absence of primary alveolar changes interfering with gas diffusion, a 95 per cent oxygen saturation in the blood of the pulmonary veins or left atrium is considered normal Several factors prevent the theoretical full saturation (100 per cent)

7 In spite of conflicting statements, the authors accept pulmonary venous return as identical with pulmonary arterial flow.

In *isolated atrial septal defect* with left-to-right shunt, the data obtained through catheterization are more reliable than in isolated ventricular septal defect or patent ductus arteriosus, because the blood obtained from the pulmonary artery is already thoroughly mixed

If there is evidence of double left-to-right shunt through both an atrial and a ventricular septal defect, the calculated figures of flow for the individual shunts are not too reliable. However, the total figure for left-to-right shunt is as reliable as it is in an isolated ventricular septal defect.

In the presence of a large left-to-right shunt through a patent ductus arteriosus, the presence of a "high" ventricular septal defect can be ruled out only with difficulty because one cannot exclude the possibility of penetration of shunted blood (with high oxygen content) from the pulmonary artery into the right ventricle, due to pulmonic insufficiency.

Calculation of the severity of a pure right-to-left shunt or a bidirectional shunt in atrial septal defects is easily made.

FORMULAS FOR CALCULATION OF A SHUNT [17]

Absence of Shunts. In the *absence of shunts*, according to Fick, the cardiac output (or estimated systemic blood flow SBF, which equals pulmonary arterial blood flow PBF) is calculated by dividing

[17] The formulas for shunts use the following symbols and abbreviations.

SIVC = O_2 content of both venae cavae, vol/100 ml (SIC × 0 40 + IVC × 0 60)
RA_{avg} = O_2 content of average right atrium, vol/100 ml
RV_{avg} = O_2 content of average right ventricle, vol/100 ml
RV
PA
PA_{avg} = O_2 content of average left and right pulmonary arteries, vol/100 ml (in patent
LA
BA =
PV
P_{RA} = right atrial pressure, mm Hg
P_{RV} = right ventricular pressure, mm Hg
P_{PA} = pulmonary arterial pressure, mm Hg
P_{BA} = brachial arterial pressure, mm Hg
Y = left-to-right shunt (Y_A = atrial level; Y_V = ventricular level)
Z = right-to-left shunt (Z_A = atrial level; Z_V = ventricular level)

the oxygen consumption by the difference between arterial and mixed venous bloods (pulmonary arterial sample).

$$SBF = PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (1)$$

Left-to-right Shunts. IN THE RIGHT ATRIUM. *Anomalous pulmonary venous return into the right atrium, or atrial septal defect with left-to-right shunt,* is suspected when

$RA_{avg} > SIVC$ (by 1.5 vol/100 ml or more)

and $RA_{avg} = PA$

Anomalous pulmonary venous return into either vena cava is suspected when the difference in oxygen content is more than 4.5 vol/100 ml between inferior and superior venae cavae.

The systemic blood flow in the first instance is calculated through formula (2), and the pulmonary flow through formula (3).

$$SBF = \frac{O_2 \times 100}{BA - SIVC} \quad ml/min \quad (2)$$

$$PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (3)$$

The left-to-right shunt can be easily obtained by subtracting systemic blood flow from pulmonary blood flow as in formula (4)

$$Y_A = PBF - SBF \quad ml/min \quad (4)$$

Also, the left-to-right shunt can be estimated from the total O_2 content of blood passing through the right atrium in 1 min as in formula (5)

$$(SBF \times SIVC) + (Y_A \times BA)$$
$$= (SBF \times RA_{avg}) + (Y_A \times RA_{avg}) \quad (5)$$

This equation can be simplifed as follows:

$$Y_A(BA - RA_{avg}) = SBF(RA_{avg} - SIVC) \quad (5a)$$

Next

$$Y_A = \frac{SBF(RA_{avg} - SIVC)}{BA - RA_{avg}} \quad ml/min \quad (5b)$$

IN THE RIGHT VENTRICLE Left-to-right shunt between ventricles is presumed if

$SIVC = RA_{avg}$ and $RV_{avg} = PA$,

but $RV_{avg} > RA_{avg}$

(by more than 1.0 vol/100 ml).

The left-to-right shunt can be estimated by using either formula (6) or (6a)

$$Y_V = PBF - SBF \quad ml/min \quad (6)$$

$$Y_V = \frac{SBF(PA - RA_{avg})}{BA - PA} \quad (6a)$$

$$= \frac{SBF(RV_{avg} - RA_{avg})}{BA - RV_{avg}} \quad ml/min \quad (6b)$$

BETWEEN AORTA AND PULMONARY ARTERY. Left-to-right shunt between the larger arteries is presumed if

$SIVC = RA_{avg} = RV_{avg}$ but $PA_{avg} > RV$

(by more than 1.0 vol/100 ml).

A left-to-right shunt through a patent ductus arteriosus or any other aortopulmonary communication can be estimated by formula (7) or (7a).

$$Y_{PA} = PBF - SBF \quad ml/min \quad (7)$$

$$Y_{PA} = SBF\frac{PA_{avg} - RA_{avg}}{BA - PA_{avg}} \quad ml/min \quad (7a)$$

The pulmonary blood flow (PBF) of formula (7) should be calculated by formula (8) from the average of samples collected from both the left and the right pulmonary arteries. It is preferable to obtain two samples of blood from each branch of the pulmonary artery (four in all).

$$PBF = \frac{O_2 \times 100}{BA - PA_{avg}} \quad ml/min \quad (8)$$

If only one pulmonary random blood sample is obtained near the orifice of the patent ductus, it may have a much higher oxygen content, and the pulmonary blood flow thus calculated may become as high as 40 liters/min. This is obviously incorrect.

In formula (7a), the use of RA_{avg} instead of RV_{avg} is based on the fact that there may be pulmonary regurgitation which would increase the oxygen content of the right ventricular samples, especially in the upper part of the ventricle.

With both atrial and ventricular defect:

$RA_{avg} > SIVC$ (by more than 1.5 vol/100 ml)

while

$RV_{avg} > RA_{avg}$ (by more than 1.0 vol/100 ml)

and

$RV_{avg} = PA$

Y_A, the left-to-right shunt through the atrial defect, can be calculated by formula (5b), Y_V, the left-to-right shunt through the ventricular defect, can be calculated by formula (9) or (9a)

$$Y_V = PBF - (SBF + Y_A) \quad ml/min \quad (9)$$

$$Y_V = \frac{(SBF + Y_A)(PA - RA_{avg})}{(BA - PA)} \quad ml/min \quad (9a)$$

Y_{A+V}, the total left-to-right shunt, can be obtained by formulas (10) and (10a):

$$Y_{A+V} = PBF - SBF \quad ml/min \quad (10)$$

$$Y_{A+V} = \frac{SBF(PA - SIVC)}{(BA - PA)} \quad ml/min \quad (10a)$$

With both ventricular septal defect and patent ductus arteriosus.

$SVC = RA_{avg}$

$RV_{avg} > RA_{avg}$ (by more than 1 0 vol/100 ml)

and

$PA_{avg} > RV_{avg}$ (by more than 1 5 vol/100 ml)

Y_V, the left-to-right shunt through the ventricular defect, can be calculated by formula (6b).

Y_{PA}, the left-to-right shunt through a patent ductus, can be calculated by formulas (11) and (11a), formula (11) is preferred for its simplicity

$$Y_{PA} = PBF - (SBF + Y_V) \quad \text{ml/min} \quad (11)$$

$$Y_{PA} = \frac{(SBF + Y_V)(PA_{avg} - RA_{avg})}{BA - PA_{avg}} \quad \text{ml/min} \quad (11a)$$

In cases of large left-to-right shunt due to patent ductus arteriosus (without any ventricular septal defect), one may find that the oxygen content of the right ventricular sample (especially if obtained from the outflow tract) is somewhat higher (1 0 vol/100 ml) than that of the samples from the right atrium and of the inflow tract (or lower part) of the right ventricle In such cases, use RA_{avg} instead of RV_{avg}.

At times it is difficult to decide whether or not there is an additional high ventricular defect or pulmonic insufficiency

PULMONARY INSUFFICIENCY *If pulmonary insufficiency* is suspected in a case *with patent ductus arteriosus*, the amount of regurgitation can also be *calculated, but the result* obtained from the average of high and mid-right ventricular samples gives *only* a rough estimate [formula (12)]

$$PI_{PA \to RV} = \frac{SBF(RV_{H+M} - RA_{avg}) \times 100}{(PA_{avg} - RV_{H+M})} \quad \text{ml/min} \quad (12)$$

Right-to-left Shunts. ATRIAL SEPTAL DEFECT WITH OR WITHOUT PULMONIC STENOSIS This shunt can be calculated by comparing the pressures of *the right ventricle and brachial artery, simultaneously* recorded The *oxygen saturation of BA* is below 92 per cent

If $\quad P_{RVS} < P_{BAS}$

there is no right-to-left shunt, provided that overriding of the aorta *is ruled* out by angiocardiography

If $\quad P_{RVS} > P_{PAS}$

pulmonic stenosis is present but still there is no shunt

If $\quad P_{RAM} = P_{RVD}$

and is slightly elevated (6 to 10 mm *Hg*) and, moreover, BA saturation is less than 92 per cent and

$$RA_{avg} = RV_{avg} = PA$$

then there is evidence of a right-to-left shunt through an atrial septal defect. Such a shunt can be calculated from formula (13b), derived from formulas (13) and (13a):

$$SBF = \frac{O_2 \times 100}{BA - PA} \quad \text{ml/min} \quad (13)$$

$$PBF = \frac{O_2 \times 100}{LA - PA} \quad \text{ml/min} \quad (13a)$$

$$Z = SBF - PBF \quad \text{ml/min} \quad (13b)$$

In formulas (14) and (14b) the calculation of right-to-left shunt is based on the total oxygen content of the blood which contributes to the mixing in the left atrium in 1 min. It is assumed that the pulmonary venous blood is 95 per cent saturated with oxygen.

$$(PBF \times BA) + (Z \times BA) = (PBF \times LA) + (Z \times PA) \quad (14)$$

$$Z(BA - PA) = PBF(LA - BA) \quad (14a)$$

$$Z = \frac{PBF(LA - BA)}{BA - PA} \quad \text{ml/min} \quad (14b)$$

VENTRICULAR SEPTAL DEFECT WITH OR WITHOUT PULMONIC STENOSIS (*TETRALOGY OF FALLOT OR EISENMENGER COMPLEX*)

If $\quad RA_{avg} = RV_{avg} = PA$

there is no left-to-right shunt

If P_{RA} mean is not elevated (less than 6 mm Hg), there is probably no right-to-left shunt through an additional atrial septal defect

If BA < 92 per cent saturated, there is right-to-left shunt

The systemic blood flow, pulmonary blood flow, and right-to-left shunt can be likewise calculated by using formulas (13), (13a), and (13b) or (14)

PATENT DUCTUS ARTERIOSUS WITH PULMONIC HYPERTENSION The calculations of the right-to-left shunt can be based *only* on certain assumptions (1) The shunt takes place from the pulmonary artery *to the* aorta at a point (ductus) which is below the opening of the left carotid artery and above that of the left subclavian artery (2) A *minor portion of the* shunted blood goes back to the aortic arch and enters the innominate artery and the two carotid arteries, while a major portion *is distributed* between left subclavian *artery and* descending aorta This second assumption, although used by some, is definitely unwarranted because,

the oxygen consumption by the difference between arterial and mixed venous bloods (pulmonary arterial sample).

$$SBF = PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (1)$$

Left-to-right Shunts. IN THE RIGHT ATRIUM. *Anomalous pulmonary venous return into the right atrium, or atrial septal defect with left-to-right shunt*, is suspected when

$$RA_{avg} > SIVC \text{ (by 1.5 vol/100 ml or more)}$$

and $$RA_{avg} = PA$$

Anomalous pulmonary venous return into either vena cava is suspected when the difference in oxygen content is more than 4.5 vol/100 ml between inferior and superior venae cavae.

The systemic blood flow in the first instance is calculated through formula (2), and the pulmonary flow through formula (3).

$$SBF = \frac{O_2 \times 100}{BA - SIVC} \quad ml/min \quad (2)$$

$$PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (3)$$

The left-to-right shunt can be easily obtained by subtracting systemic blood flow from pulmonary blood flow as in formula (4)

$$Y_A = PBF - SBF \quad ml/min \quad (4)$$

Also, the left-to-right shunt can be estimated from the total O_2 content of blood passing through the right atrium in 1 min as in formula (5)

$$(SBF \times SIVC) + (Y_A \times BA)$$
$$= (SBF \times RA_{avg}) + (Y_A \times RA_{avg}) \quad (5)$$

This equation can be simplified as follows.

$$Y_A(BA - RA_{avg}) = SBF(RA_{avg} - SIVC) \quad (5a)$$

Next

$$Y_A = \frac{SBF(RA_{avg} - SIVC)}{BA - RA_{avg}} \quad ml/min \quad (5b)$$

IN THE RIGHT VENTRICLE. Left-to-right shunt between ventricles is presumed if

$$SIVC = RA_{avg} \quad \text{and} \quad RV_{avg} = PA,$$

but $$RV_{avg} > RA_{avg}$$

(by more than 1.0 vol/100 ml).

The left-to-right shunt can be estimated by using either formula (6) or (6a)

$$Y_V = PBF - SBF \quad ml/min \quad (6)$$

$$Y_V = \frac{SBF(PA - RA_{avg})}{BA - PA} \quad (6a)$$

$$= \frac{SBF(RV_{avg} - RA_{avg})}{BA - RV_{avg}} \quad ml/min \quad (6b)$$

BETWEEN AORTA AND PULMONARY ARTERY. Left-to-right shunt between the larger arteries is presumed if

$$SIVC = RA_{avg} = RV_{avg} \quad \text{but} \quad PA_{avg} > RV$$

(by more than 1.0 vol/100 ml).

A left-to-right shunt through a patent ductus arteriosus or any other aortopulmonary communication can be estimated by formula (7) or (7a).

$$Y_{PA} = PBF - SBF \quad ml/min \quad (7)$$

$$Y_{PA} = SBF \frac{PA_{avg} - RA_{avg}}{BA - PA_{avg}} \quad ml/min \quad (7a)$$

The pulmonary blood flow (PBF) of formula (7) should be calculated by formula (8) from the average of samples collected from both the left and the right pulmonary arteries. It is preferable to obtain two samples of blood from each branch of the pulmonary artery (four in all).

$$PBF = \frac{O_2 \times 100}{BA - PA_{avg}} \quad ml/min \quad (8)$$

If only one pulmonary random blood sample is obtained near the orifice of the patent ductus, it may have a much higher oxygen content, and the pulmonary blood flow thus calculated may become as high as 40 liters/min. This is obviously incorrect

In formula (7a), the use of RA_{avg} instead of RV_{avg} is based on the fact that there may be pulmonary regurgitation which would increase the oxygen content of the right ventricular samples, especially in the upper part of the ventricle

With both atrial and ventricular defect.

$$RA_{avg} > SIVC \text{ (by more than 1.5 vol/100 ml)}$$

while

$$RV_{avg} > RA_{avg} \text{ (by more than 1.0 vol/100 ml)}$$

and

$$RV_{avg} = PA$$

Y_A, the left-to-right shunt through the atrial defect, can be calculated by formula (5b); Y_V, the left-to-right shunt through the ventricular defect, can be calculated by formula (9) or (9a)

$$Y_V = PBF - (SBF + Y_A) \quad ml/min \quad (9)$$

$$Y_V = \frac{(SBF + Y_A)(PA - RA_{avg})}{(BA - PA)} \quad ml/min \quad (9a)$$

Y_{A+V}, the total left-to-right shunt, can be obtained by formulas (10) and (10a):

$$Y_{A+V} = PBF - SBF \quad ml/min \quad (10)$$

$$Y_{A+V} = \frac{SBF(PA - SIVC)}{(BA - PA)} \quad ml/min \quad (10a)$$

With both ventricular septal defect and patent ductus arteriosus:

$$SIVC = RA_{avg}$$

$$RV_{avg} > RA_{avg} \text{ (by more than 1.0 vol/100 ml)}$$

and

$$PA_{avg} > RV_{avg} \text{ (by more than 1.5 vol/100 ml)}$$

Y_V, the left-to-right shunt through the ventricular defect, can be calculated by formula (6b).

Y_{PA}, the left-to-right shunt through a patent ductus, can be calculated by formulas (11) and (11a), formula (11) is preferred for its simplicity.

$$Y_{PA} = PBF - (SBF + Y_V) \quad \text{ml/min} \quad (11)$$

$$Y_{PA} = \frac{(SBF - Y_V)(PA_{avg} - RA_{avg})}{BA - PA_{avg}} \quad \text{ml/min} \quad (11a)$$

In cases of large left-to-right shunt due to patent ductus arteriosus (without any ventricular septal defect), one may find that the oxygen content of the right ventricular sample (especially if obtained from the outflow tract) is somewhat higher (1.0 vol/100 ml) than that of the samples from the right atrium and of the inflow tract (or lower part) of the right ventricle. In such cases, use RA_{avg} instead of RV_{avg}.

At times it is difficult to decide whether or not there is an additional high ventricular defect or pulmonic insufficiency.

PULMONARY INSUFFICIENCY If *pulmonary insufficiency* is suspected in a case *with patent ductus arteriosus*, the amount of regurgitation can also be calculated, but the result obtained from the average of high and mid-right ventricular samples gives only a rough estimate [formula (12)]

$$PI_{PA-RV} = \frac{SBF(RV_{H-M} - RA_{avg}) \times 100}{(PA_{avg} - RV_{H-M})} \quad \text{ml/min} \quad (12)$$

Right-to-left Shunts. ATRIAL SEPTAL DEFECT WITH OR WITHOUT PULMONIC STENOSIS. This shunt can be calculated by comparing the pressures of the right ventricle and brachial artery, simultaneously recorded. The oxygen saturation of BA is below 92 per cent.

If $$P_{RVS} < P_{BAS}$$

there is no right-to-left shunt, provided that overriding of the aorta is ruled out by angiocardiography

If $$P_{RVS} > P_{BAS}$$

pulmonic stenosis is present but still there is no shunt.

If $$P_{RAM} = P_{RVD}$$

and is slightly elevated (6 to 10 mm Hg) and, moreover, BA saturation is less than 92 per cent and

$$RA_{avg} = RV_{avg} = PA$$

then there is evidence of a right-to-left shunt through an atrial septal defect. Such a shunt can be calculated from formula (13b), derived from formulas (13) and (13a):

$$SBF = \frac{O_2 \times 100}{BA - PA} \quad \text{ml/min} \quad (13)$$

$$PBF = \frac{O_2 \times 100}{LA - PA} \quad \text{ml/min} \quad (13a)$$

$$Z = SBF - PBF \quad \text{ml/min} \quad (13b)$$

In formulas (14) and (14b) the calculation of right-to-left shunt is based on the total oxygen content of the blood which contributes to the mixing in the left atrium in 1 min. It is assumed that the pulmonary venous blood is 95 per cent saturated with oxygen.

$$(PBF \times BA) + (Z \times BA) = (PBF \times LA) + (Z \times PA) \quad (14)$$

$$Z(BA - PA) = PBF(LA - BA) \quad (14a)$$

$$Z = \frac{PBF(LA - BA)}{BA - PA} \quad \text{ml/min} \quad (14b)$$

VENTRICULAR SEPTAL DEFECT WITH OR WITHOUT PULMONIC STENOSIS (TETRALOGY OF FALLOT OR EISENMENGER COMPLEX)

If $$RA_{avg} = RV_{avg} = PA$$

there is no left-to-right shunt.

If P_{RA} mean is not elevated (less than 6 mm Hg), there is probably no right-to-left shunt through an additional atrial septal defect.

If BA < 92 per cent saturated, there is right-to-left shunt.

The systemic blood flow, pulmonary blood flow, and right-to-left shunt can be likewise calculated by using formulas (13), (13a), and (13b) or (14).

PATENT DUCTUS ARTERIOSUS WITH PULMONIC HYPERTENSION. The calculations of the right-to-left shunt can be based only on certain assumptions. (1) The shunt takes place from the pulmonary artery to the aorta at a point (ductus) which is below the opening of the left carotid artery and above that of the left subclavian artery. (2) A minor portion of the shunted blood goes back to the aortic arch and enters the innominate artery and the two carotid arteries, while a major portion is distributed between left subclavian artery and descending aorta. This second assumption, although used by some, is definitely unwarranted because,

the oxygen consumption by the difference between arterial and mixed venous bloods (pulmonary arterial sample).

$$SBF = PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (1)$$

Left-to-right Shunts. IN THE RIGHT ATRIUM. *Anomalous pulmonary venous return into the right atrium, or atrial septal defect with left-to-right shunt,* is suspected when

$RA_{avg} > SIVC$ (by 1.5 vol/100 ml or more)

and $RA_{avg} = PA$

Anomalous pulmonary venous return into either vena cava is suspected when the difference in oxygen content is more than 4.5 vol/100 ml between inferior and superior venae cavae.

The systemic blood flow in the first instance is calculated through formula (2), and the pulmonary flow through formula (3).

$$SBF = \frac{O_2 \times 100}{BA - SIVC} \quad ml/min \quad (2)$$

$$PBF = \frac{O_2 \times 100}{BA - PA} \quad ml/min \quad (3)$$

The left-to-right shunt can be easily obtained by subtracting systemic blood flow from pulmonary blood flow as in formula (4)

$$Y_A = PBF - SBF \quad ml/min \quad (4)$$

Also, the left-to-right shunt can be estimated from the total O_2 content of blood passing through the right atrium in 1 min as in formula (5)

$$(SBF \times SIVC) + (Y_A \times BA) = (SBF \times RA_{avg}) + (Y_A \times RA_{avg}) \quad (5)$$

This equation can be simplified as follows

$$Y_A(BA - RA_{avg}) = SBF(RA_{avg} - SIVC) \quad (5a)$$

Next

$$Y_A = \frac{SBF(RA_{avg} - SIVC)}{BA - RA_{avg}} \quad ml/min \quad (5b)$$

IN THE RIGHT VENTRICLE. Left-to-right shunt between ventricles is presumed if

$SIVC = RA_{avg}$ and $RV_{avg} = PA$,

but $RV_{avg} > RA_{avg}$

(by more than 1.0 vol/100 ml).

The left-to-right shunt can be estimated by using either formula (6) or (6a)

$$Y_V = PBF - SBF \quad ml/min \quad (6)$$

$$Y_V = \frac{SBF(PA - RA_{avg})}{BA - PA} \quad (6a)$$

$$= \frac{SBF(RV_{avg} - RA_{avg})}{BA - RV_{avg}} \quad ml/min \quad (6b)$$

BETWEEN AORTA AND PULMONARY ARTERY. Left-to-right shunt between the larger arteries is presumed if

$SIVC = RA_{avg} = RV_{avg}$ but $PA_{avg} > RV$

(by more than 1.0 vol/100 ml).

A left-to-right shunt through a patent ductus arteriosus or any other aortopulmonary communication can be estimated by formula (7) or (7a).

$$Y_{PA} = PBF - SBF \quad ml/min \quad (7)$$

$$Y_{PA} = SBF\frac{PA_{avg} - RA_{avg}}{BA - PA_{avg}} \quad ml/min \quad (7a)$$

The pulmonary blood flow (PBF) of formula (7) should be calculated by formula (8) from the average of samples collected from both the left and the right pulmonary arteries. It is preferable to obtain two samples of blood from each branch of the pulmonary artery (four in all).

$$PBF = \frac{O_2 \times 100}{BA - PA_{avg}} \quad ml/min \quad (8)$$

If only one pulmonary random blood sample is obtained near the orifice of the patent ductus, it may have a much higher oxygen content, and the pulmonary blood flow thus calculated may become as high as 40 liters/min. This is obviously incorrect.

In formula (7a), the use of RA_{avg} instead of RV_{avg} is based on the fact that there may be pulmonary regurgitation which would increase the oxygen content of the right ventricular samples, especially in the upper part of the ventricle.

With both atrial and ventricular defect

$RA_{avg} > SIVC$ (by more than 1.5 vol/100 ml)

while

$RV_{avg} > RA_{avg}$ (by more than 1.0 vol/100 ml)

and

$RV_{avg} = PA$

Y_A, the left-to-right shunt through the atrial defect, can be calculated by formula (5b), Y_V, the left-to-right shunt through the ventricular defect, can be calculated by formula (9) or (9a)

$$Y_V = PBF - (SBF + Y_A) \quad ml/min \quad (9)$$

$$Y_V = \frac{(SBF + Y_A)(PA - RA_{avg})}{(BA - PA)} \quad ml/min \quad (9a)$$

Y_{A+V}, the total left-to-right shunt, can be obtained by formulas (10) and (10a).

$$Y_{A+V} = PBF - SBF \quad ml/min \quad (10)$$

$$Y_{A+V} = \frac{SBF(PA - SIVC)}{(BA - PA)} \quad ml/min \quad (10a)$$

13

Cardiac output, blood volume, and heart volume

Cardiac Output

ARTHUR GROLLMAN

Determination of Blood Volume

CUSTAV NYLIN AND SVEN HEDLUND

Roentgenographic Heart Volume Determination

GUSTAV NYLIN

CARDIAC OUTPUT

HISTORICAL BACKGROUND

The importance of the cardiac output in promoting an adequate understanding of problems relating to the circulation in health and disease has long been recognized In fact, it was from a consideration of the capacity of the ventricles that Harvey concluded that the amount of blood pumped by the heart exceeded that which could possibly be formed from the food, thus leading to his discovery of the function of the heart and circulation. Harvey also appreciated the variability of the cardiac output and enumerated conditions which he assumed would modify this output. Subsequent workers estimated the cardiac output on the basis of the capacity of the ventricles as measured after death Interestingly enough, their average estimates were not far from the values accepted today Thus Sénac estimated the systolic output to be about 30 ml, Young, 45 ml, Haller, LaPlace, and others, 60 ml, Borelli, 90 ml

The earliest experimental attempts to determine the cardiac output were indirect and based on measurements of the rate at which blood moves in the arteries. Volkmann utilized a *hemodrometer*, an instrument introduced into an artery to determine the rate at which a given volume of water is displaced by the blood flow. He estimated the systolic output of man to be 188 ml. With the introduction of the *stromuhr* by Ludwig (1867), it was possible to measure directly the output of the heart (in lower animals) by introducing this instrument into the aorta. From these measurements, various investigators estimated the systolic output in man to be 50 to 80 ml

Direct determination of the cardiac output in the intact animal was accomplished by Fick (1870) The Fick principle, which is the basis for the direct determination of the cardiac output, was first applied to dogs by Gréhant and Quinquaud (1886) and to the horse by Zunz and Hagemann (1898) in their classic study It was subsequently applied to various other laboratory animals and to man, and is the basis for the determination of the cardiac output by the use of foreign gases as well as by right heart catheterization Although the principles underlying present-day techniques for measuring cardiac output had been well established by the turn of the twentieth century, they were not brought to practical use on man for a quarter of a century.

DEFINITIONS

The term *cardiac output* refers to the quantity of blood ejected per minute by each ventricle, since over any considerable period of

in some cases, no evidence of low oxygen saturation can be found in either the left arm or the left ear lobe. Therefore, as there is no accurate method of ascertaining this distribution of blood, accurate mathematical calculation of the amount of shunt is impossible.

Bidirectional Shunts (Left-to-right plus Right-to-left Shunts). ATRIAL SEPTAL DEFECT WITH OR WITHOUT PULMONIC STENOSIS. The calculations are based on the values of the total oxygen content which contributes to the mixing in the left and right atria in 1 min. It is assumed that

$$RA_{avg} = RV_{avg} = PA$$

and that LA is at 95 per cent saturation. Formulas (15) and (16) are used.

$$PBF = \frac{O_2 \times 100}{LA - PA} \quad ml/min \qquad (15)$$

$$SBF = \frac{O_2 \times 100}{BA - SIVC} \quad ml/min \qquad (16)$$

In the *right atrium*, the amount of blood which contributes to the mixing in 1 min is calculated by using formulas (17), (17a), (17b), and (17c).

$$(SBF - Z)SIVC + (Y \times LA) = (SBF - Z + Y)PA \qquad (17)$$

$$(SBF \times SIVC) - (Z \times SIVC) + (Y \times LA) = SBF \times PA - Z \times PA + Y \times PA \qquad (17a)$$

$$Y(LA - PA) = SBF(PA - SIVC) + Z(SIVC - PA) \qquad (17b)$$

$$Y = \frac{SBF(PA - SIVC) + Z(SIVC - PA)}{LA - PA} \qquad (17c)$$

In the *left atrium*, the amount of blood which contributes to the mixing in 1 min is calculated by using formulas (18), (18a), (18b), and (18c):

$$(PBF - Y)LA + (Z \times SIVC) = (PBF - Y + Z)BA \qquad (18)$$

$$(PBF \times LA) - (Y \times LA) + (Z \times SIVC) = (PBF \times BA) - (Y \times BA) + (Z \times BA) \qquad (18a)$$

$$Z(BA - SIVC) = PBF(LA - BA) + Y(BA - LA) \qquad (18b)$$

$$Z = \frac{PBF(LA - BA) + Y(BA - LA)}{(BA - SIVC)} \qquad (18c)$$

Substitute (18c) into (17c) to derive formula (19):

$$Y = \frac{\left[SBF(PA - SIVC) + \left(\frac{PBF(LA - BA) + Y(BA - LA)}{BA - SIVC}\right)(SIVC - PA)\right]}{(LA - PA)} \qquad (19)$$

Knowing pulmonary flow, effective pulmonary flow, and systemic flow, one can use Bing's formulas [(20) and (21)] for calculating right-to-left and left-to-right shunts. The "effective pulmonary flow" EPBF will be described below.

$$Y = PBF - EPBF \quad ml/min \qquad (20)$$

$$Z = SBF - EPBF \quad ml/min \qquad (21)$$

EISENMENGER COMPLEX. In this case

$$SIVC = RA_{avg} \quad \text{and} \quad RV_{avg} > RA_{avg}$$

but

$$RV_{avg} = PA$$

As in atrial septal defect with bidirectional shunt, one can use formulas (15), (16), (17c), (18c), (19), or (20) and (21) in order to calculate the left-to-right (Y) and right-to-left (Z) shunts.

In order to obtain a more reliable result, it is advisable to substitute the SIVC for RA_{avg}.

The calculation of the "effective pulmonary blood flow" EPBF was advocated by Bing, and it is defined as the amount of mixed venous blood which, having returned to the heart from the systemic circulation, eventually reaches the pulmonary capillaries. Normally, the effective pulmonary blood flow equals pulmonary arterial flow, except when bidirectional shunts are present: as in some cases of atrial septal defect complicated by pulmonic stenosis, and in cases of the Eisenmenger complex.

Formula (22) is useful in the former cases and (23) in the latter.

$$EPBF = \frac{O_2 \times 100}{PV - SIVC} \quad ml/min \qquad (22)$$

$$EPBF = \frac{O_2 \times 100}{LA - RA_{avg}} \quad ml/min \qquad (23)$$

PULMONIC STENOSIS. Especially in cases of tetralogy of Fallot, pulmonic stenosis may be accompanied by large collateral (bronchial) circulation or by a patent ductus arteriosus. In such cases, total pulmonary blood flow or pulmonary capillary blood flow is larger than the main pulmonary arterial blood flow. The former can only be calculated by indirect means, and the result is only a rough estimate.

f the blood passing that location over the period f sampling Both cardiac- and respiratory-cyclic changes in the above quantities are capable of introducing large errors into the calculation of the cardiac output. When oxygen, for example, is used for a reference substance, it must be ascertained that no significant cyclic changes in the arteriovenous oxygen difference coincide with flow-rate changes At ordinary pulmonary oxygen tension the arteriovenous oxygen difference is fairly constant but this is not true during the respiratory cycle at low oxygen tensions In animals breathing low oxygen mixtures, for example, the usual Fick formula underestimates the true cardiac output considerably (Nahas et al) The validity of the direct Fick method in the presence of an abnormally low alveolar oxygen tension is thus questionable. Large errors may also be introduced in the case of shunts of the heart and large vessels. Thus, in patent ductus arteriosus, the ordinary Fick method will yield deceptively high values

Despite the above objections, the direct Fick method has yielded values which, in general, conform to those obtained by other procedures and have added greatly to the general knowledge of the cardiac output, particularly under circumstances where other procedures are not applicable The procedure is of most value, however, for determining pressure relationships in the cardiovascular system For this purpose, as described elsewhere, it is indispensable; for the determination of the cardiac output, other available, less formidable, and less hazardous procedures are preferable.

INDIRECT METHODS BASED ON THE FICK PRINCIPLE

Because the early observers hesitated to penetrate the right chamber of the heart in order to obtain samples of mixed venous blood, their efforts to determine the cardiac output in man were directed towards finding an indirect procedure whereby the Fick principle could be applied. A variety of methods was introduced for obtaining samples of respiratory gases which were in equilibrium with mixed venous blood Although these procedures, when properly carried out, gave results which were probably accurate, the difficulty of applying these, the necessity for complicated respiratory maneuvers, the inapplicability of the methods to all patients, and certain errors intrinsic in these methods led to their being only occasionally used at present (Forsander).

Methods Based on the Use of a Foreign Gas. More successful, and avoiding the disadvantages of the various respiratory procedures, were methods involving the use of a foreign gas. Of these, the use of acetylene proved to be technically advantageous and was widely applied. In the acetylene procedure, a mixture of this gas and air was rebreathed from a rubber bag and after equilibration of the mixture in the lung-bag system, samples were withdrawn into evacuated tubes. Analysis of the content of these gases and a basal metabolic oxygen consumption determined in the usual manner afforded the data necessary for calculating the cardiac output (Grollman).

The results obtained by the application of the acetylene method are consistent, but are lower than those now accepted on the basis of determinations by the direct Fick and dye-dilution methods. Part of this discrepancy is undoubtedly due to recirculation of blood through the shorter vascular channels (Werko et al)

Baumann and Grollman, by analysis of blood obtained from puncture of the right heart found 57 per cent of acetylene in the sample at 13 to 20 sec after beginning the rebreathing. Comparable results were obtained by Starr and Collins in dogs and by Werko et al., who found no acetylene in the blood until between 10 and 15 sec had passed, and then it appeared in a concentration corresponding to a content in the alveolar air of 0 4 to 0.5 vol/100 ml air. Another reason for the lower values obtained by the acetylene procedure is the fact that the avoidance of manipulations requiring arterial or venous punctures permits the attainment of truly basal levels The procedure determines the cardiac output obtaining prior to beginning the rebreathing and thus reflects the condition of the circulation at truly basal levels and complete bodily rest and relaxation.

The chief drawback to the acetylene method is the necessity for the subject to undergo certain respiratory maneuvers and the fact that the procedure is inapplicable in many clinical conditions where recirculation occurs to too great an extent in the time necessary for attaining homogeneous mixture in the lung-bag system For this reason it has been largely abandoned for the direct Fick method and for

time precisely the same quantity of blood is ejected by each ventricle. The less appropriate term *minute volume*, a literal translation of the German *Minutenvolumen*, has also been widely used but has been largely discarded in the recent literature.

The *stroke volume* or *systolic output* is the amount of blood ejected with each heart beat. Since the cardiac output is related to the body size or more specifically to the protoplasmic activity of the individual, it is usually expressed in terms of square meters of body surface, or *cardiac index*, a term introduced by the author (1928). An expression in terms of the fat-free body weight might be more appropriate but, considering the difficulties of such a determination, is impractical at the present time.

DIRECT METHODS

Direct methods for determining the cardiac output are based on the Fick principle which states that the oxygen uptake divided by the arteriovenous oxygen difference (in milliliters/liter of blood) is equal to the volume of blood pumped by the heart per minute. The first application of this procedure to the human being was made in 1929 when Forssmann catheterized the right heart to obtain mixed venous blood. This procedure, at the time of its introduction, appeared too hazardous and formidable for general use and was superseded by puncture of the right ventricle. By using the latter procedure, Baumann and Grollman established the accuracy of the indirect acetylene method on man. Several subsequent studies in various laboratories obtained useful data in the clinic by utilizing the procedure of cardiac puncture.

Cardiac Catheterization. The widespread application of right heart catheterization was inaugurated by Cournand and his coworkers a decade later. In this procedure, mixed venous blood from the right heart and an arterial sample collected simultaneously from the femoral or brachial artery are analyzed for their oxygen content. The arteriovenous oxygen difference thus obtained, with the oxygen uptake, as determined by the usual spirometric technique, permits the calculation of the cardiac output.

The principal objections to the direct Fick method are the hazard and violence of a technique requiring cardiac catheterization. There has always been a question as to how much such a procedure, even when tolerated by the patient and performed under the most tranquil of conditions, might nevertheless disturb the patient, so that basal values would not be obtained. This objection is particularly valid if one considers the ease with which the cardiac output may be increased by psychological disturbance. Thus, simple puncture of the brachial artery was found (Baumann and Grollman) to increase the cardiac output by a liter or more over its basal level, even in apparently undisturbed patients. The catheterization technique also involves a slight but definite hazard to the patient. Thus, in patients suffering from pulmonary hypertension, sudden death has been reported in 3 patients. Such deaths are attributable to the stimulation of receptors in the wall of the pulmonary artery and vein, or to acute failure of the right heart.

Despite the apparent directness of the method, cardiac output and cardiac index, as determined by catheterization of the heart, have shown marked variations for normal healthy individuals at rest, not only by different observers, but even in the same laboratory. Thus, in 14 individuals, Gray et al. (1947) observed a cardiac index of 2.1 to 3.7 with a mean of 2.8 liters/min/m² of body surface, whereas Bing et al., after testing 7 individuals, reported a mean cardiac index of 4.76, almost 75 per cent higher than that of a previous series (Bartels et al.). Other observers have found even more discordant results with wide variations. For example, Nickerson et al. (1945), in a series of 54 individuals observed a cardiac index which varied from 1.5 to 5.9. It would seem most logical to attribute these wide variations to the inevitable psychological disturbance induced in the patient by the procedure, since the intrinsic errors of the method are not great (Werko et al.). The generally accepted value of 3.1 liters/min/m² of body surface as the resting basal cardiac index is probably about 0.5 liter higher than that obtaining under truly basal resting conditions.

A large systematic discrepancy has also been noted between the cardiac output measurements made by the direct Fick procedure and those made by the dye-dilution method under conditions of low-oxygen-tension breathing (Nahas, Haddy and Visscher, Visscher and Johnson). This results from the fact that certain important implicit assumptions not stated by Fick are commonly ignored in applications of the usual blood flow equation. The Fick equation may properly be used, employing mean rather than instantaneous values for arteriovenous differences for the reference substance and for the velocity of flow, only if one or both of these quantities are constant over the time of observation. However, there are numerous situations in which neither is constant, thus giving rise to certain errors. The sample of blood drawn from a vessel in which flow varies over time is a time-average sample and not a volume-average sample

of the blood passing that location over the period of sampling. Both cardiac- and respiratory-cyclic changes in the above quantities are capable of introducing large errors into the calculation of the cardiac output. When oxygen, for example, is used for a reference substance, it must be ascertained that no significant cyclic changes in the arteriovenous oxygen difference coincide with flow-rate changes At ordinary pulmonary oxygen tension the arteriovenous oxygen difference is fairly constant but this is not true during the respiratory cycle at low oxygen tensions. In animals breathing low oxygen mixtures, for example, the usual Fick formula underestimates the true cardiac output considerably (Nahas et al) The validity of the direct Fick method in the presence of an abnormally low alveolar oxygen tension is thus questionable Large errors may also be introduced in the case of shunts of the heart and large vessels. Thus, in patent ductus arteriosus, the ordinary Fick method will yield deceptively high values

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Baumann and Grollman, by analysis of blood obtained from puncture of the right heart found 5 7 per cent of acetylene in the sample at 13 to 20 sec after beginning the rebreathing Comparable results were obtained by Starr and Collins in dogs and by Werko et al., who found no acetylene in the blood until between 10 and 15 sec had passed, and then it appeared in a concentration corresponding to a content in the alveolar air of 0 4 to 0 5 vol/100 ml air Another reason for the lower values obtained by the acetylene procedure is the fact that the avoidance of manipulations requiring arterial or venous punctures permits the attainment of truly basal levels The procedure determines the cardiac output obtaining prior to beginning the rebreathing and thus reflects the condition of the circulation at truly basal levels and complete bodily rest and relaxation

The chief drawback to the acetylene method is the necessity for the subject to undergo certain respiratory maneuvers and the fact that the procedure is inapplicable in many clinical conditions where recirculation occurs to too great an extent in the time necessary for attaining homogeneous mixture in the lung-bag system. For this reason it has been largely abandoned for the direct Fick method and for

time precisely the same quantity of blood is ejected by each ventricle. The less appropriate term *minute volume*, a literal translation of the German *Minutenvolumen*, has also been widely used but has been largely discarded in the recent literature.

The *stroke volume* or *systolic output* is the amount of blood ejected with each heart beat. Since the cardiac output is related to the body size or more specifically to the protoplasmic activity of the individual, it is usually expressed in terms of square meters of body surface, or *cardiac index*, a term introduced by the author (1928). An expression in terms of the fat-free body weight might be more appropriate but, considering the difficulties of such a determination, is impractical at the present time.

DIRECT METHODS

Direct methods for determining the cardiac output are based on the Fick principle which states that the oxygen uptake divided by the arteriovenous oxygen difference (in milliliters/liter of blood) is equal to the volume of blood pumped by the heart per minute. The first application of this procedure to the human being was made in 1929 when Forssmann catheterized the right heart to obtain mixed venous blood This procedure, at the time of its introduction, appeared too hazardous and formidable for general use and was superseded by puncture of the right ventricle By using the latter procedure, Baumann and Grollman established the accuracy of the indirect acetylene method on man Several subsequent studies in various laboratories obtained useful data in the clinic by utilizing the procedure of cardiac puncture.

Cardiac Catheterization. The widespread application of right heart catheterization was inaugurated by Cournand and his coworkers a decade later. In this procedure, mixed venous blood from the right heart and an arterial sample collected simultaneously from the femoral or brachial artery are analyzed for their oxygen content The arteriovenous oxygen difference thus obtained, with the oxygen uptake, as determined by the usual spirometric technique, permits the calculation of the cardiac output

The principal objections to the direct Fick method are the hazard and violence of a technique requiring cardiac catheterization. There has always been a question as to how much such a procedure, even when tolerated by the patient and performed under the most tranquil of conditions, might nevertheless disturb the patient, so that basal values would not be obtained. This objection is particularly valid if one considers the ease with which the cardiac output may be increased by psychological disturbance. Thus, simple puncture of the brachial artery was found (Baumann and Grollman) to increase the cardiac output by a liter or more over its basal level, even in apparently undisturbed patients. The catheterization technique also involves a slight but definite hazard to the patient. Thus, in patients suffering from pulmonary hypertension, sudden death has been reported in 3 patients. Such deaths are attributable to the stimulation of receptors in the wall of the pulmonary artery and vein, or to acute failure of the right heart.

Despite the apparent directness of the method, cardiac output and cardiac index, as determined by catheterization of the heart, have shown marked variations for normal healthy individuals at rest, not only by different observers, but even in the same laboratory. Thus, in 14 individuals, Gray et al. (1947) observed a cardiac index of 2.1 to 3.7 with a mean of 2 8 liters/min/m² of body surface, whereas Bing et al, after testing 7 individuals, reported a mean cardiac index of 4.76, almost 75 per cent higher than that of a previous series (Bartels et al). Other observers have found even more discordant results with wide variations. For example, Nickerson et al (1945), in a series of 54 individuals observed a cardiac index which varied from 1 5 to 5.9. It would seem most logical to attribute these wide variations to the inevitable psychological disturbance induced in the patient by the procedure, since the intrinsic errors of the method are not great (Werko et al.). The generally accepted value of 3 1 liters/min/m² of body surface as the resting basal cardiac index is probably about 0 5 liter higher than that obtaining under truly basal resting conditions.

A large systematic discrepancy has also been noted between the cardiac output measurements made by the direct Fick procedure and those made by the dye-dilution method under conditions of low-oxygen-tension breathing (Nahas, Haddy and Visscher, Visscher and Johnson). This results from the fact that certain important implicit assumptions not stated by Fick are commonly ignored in applications of the usual blood flow equation. The Fick equation may properly be used, employing mean rather than instantaneous values for arteriovenous differences for the reference substance and for the velocity of flow, only if one or both of these quantities are constant over the time of observation. However, there are numerous situations in which neither is constant, thus giving rise to certain errors The sample of blood drawn from a vessel in which flow varies over time is a time-average sample and not a volume-average sample

than the average output over a number of beats as in the available methods. The physical methods which have been used include measurements of the pulse form, blood pressure measurements, capacitance changes, and the procedures now to be described.

X-RAY. Several attempts have been made to utilize the area of the cardiac shadow, as determined by x-ray, as a means to measure the systolic output. By subtracting the cardiac volume at the end of systole from that at the end of diastole one obtains the systolic output. Utilizing this procedure and Bardeen's formula for calculating the volume of the heart from its silhouette, Eyster and Meek found the systolic output of normal individuals to be about 80 ml during rest and 94 ml during exercise. This corresponded to a cardiac output of 5.9 liters at rest and 10.8 liters during moderate exercise. Since there is no exact relationship between the area of the cardiac projection in a single plane and the changes in volume of the heart, this procedure can offer only a rough approximation of the cardiac output.

PULSE-WAVE VELOCITY The first attempt to determine the cardiac output by an indirect physical method was that by Fick and Hoorweg, who estimated the cardiac output from the expansion of the carotid artery occurring with each pulse beat. Wave mechanics permit one to develop integral equations expressing the amount of blood circulating through the body as a function of the velocity of the pulse wave and the pressure changes occurring in the arterial system. Broemser and Ranke, utilizing Otto Frank's equation, applied this principle in determining the cardiac output, but their results were subject to considerable uncertainty. Warner and his colleagues have also attempted to utilize various characteristics of the arterial pressure-pulse wave to follow rapid changes in stroke volume.

The chief difficulty in attempting to measure cardiac output from the pressure-pulse wave in the human being is the unpredictable individual variation in the diastolic size and elasticity of the aorta and large arteries. If the cardiac output is determined by an independent method, such as the Fick or dye-dilution method, during a steady state, a factor relating change in pressure to change in volume may be determined at the outset for each subject. In this way one can derive equations for estimating the stroke volume from a recording of one central and one peripheral arterial pressure-pulse wave (Starr et al.). Such an empirically derived formula has been used by Hendricks and Quilligan to obtain instantaneous values of the cardiac output during the various stages of parturition. The values thus obtained when compared with the dye-injection method showed an agreement within 25 per cent in 30 determinations carried out on 23 subjects. However, variations as great as 45 per cent were obtained in individual cases. The procedure must thus be considered as giving, at best, only a crude approximation of the true value.

ELECTROKYMOGRAPHY The stroke volume may be estimated from the changes in the intensity of x-rays reaching a fluorescent screen and photomultiplier tube as recorded by the electrokymograph (Chap. 8). When the heart changes in thickness, the absorption of x-rays is altered, this change affects, in turn, the amplitude of the photoelectric signal. However, to estimate the cardiac stroke from the electrokymographic records, one must take into account not only changes in the size of the heart but also the inward movements of the ventricles. Because of the unusual positional movement of the heart, Ring et al. were unable in 10 out of 43 human subjects to predict the cardiac output satisfactorily from electrokymographic measurements.

These authors utilized the formula

$$\text{Stroke volume} = 13.6DT$$

where D = transverse diameter of the heart, cm
T = average inward movement of the heart, cm

Comparison of the results with the dye-injection method gave a standard deviation of ± 17 per cent in those subjects in whom the formula proved satisfactory and where suitable records were obtained.

The Ballistocardiogram. Inasmuch as ballistocardiography is described in another section (Chap. 4), it will only be referred to here in connection with its use for estimating the cardiac output. The ballistocardiogram was first suggested for measuring cardiac output by Douglas, Haldane, Henderson, and Schneider, who used a very primitive form of such an instrument to measure the circulation

the recent modifications of the dye-injection procedure.

Injection Methods. The injection methods for determining the cardiac output and volume of blood in limited sections of the cardiovascular system are based on a principle first suggested by Stewart (1897) and elaborated by Henriques (1913) and Hamilton and his coworkers (1929). As indicators, Evans blue dye (T-1824), Bromsulphalein, red blood corpuscles tagged with a radioactive isotope, blood albumin tagged with I^{131}, or other similar agents have been utilized. The principle of the procedure is based on the fact that curves describing the concentration of the injected indicator in the arterial blood during its first passage through the circulation may be used to calculate the cardiac output. The technique requires the collection of arterial samples serially at intervals of 1 or 2 sec. Analysis of these samples permits the construction of a time vs. concentration curve, the area under which is related to the cardiac output per unit of time. From such a curve one can also calculate the central blood volume, i.e., the volume of blood between the point of injection and the point of arterial sampling, the earliest and mean circulation times, and, to a less satisfactory degree, the disappearance time of the dye.

The following equation is used for calculating the cardiac output by this method (Hamilton et al., Meier and Zierler).

$$CO = 60I/cT$$

where CO = cardiac output in ml/min

I = amount of dye or other substance injected, mg

c = mean concentration of the dye obtained by planimetric integration of the curve

T = total duration of the curve extrapolated to the base line, sec

The most serious drawback to this method is the tediousness of the analysis and calculations (Dow, Lewis). Its main sources of error lie in the arbitrary extrapolation of the descending limb of the curve to the base line, a procedure which is made necessary by the appearance of a secondary hump in the curve which is attributable to recirculation (Theilen et al.). An advantage to the method is that, unlike the direct Fick or acetylene methods, it does not require determination of the oxygen consumption. The tediousness of the injection method has been in part overcome by the use of a *cuvette oximeter* which records changes in dye concentration of arterial blood passing through it. However, when using the cuvette for measuring dye concentration, both red and infrared transmission should be measured since the injection of the dye (T-1824) increases the transmission of infrared light, probably as the result of some change occurring in the erythrocytes (Falholt and Kaiser). Attempts have also been made to use the ear oximeter to record changes in concentration of dye in blood similar to those obtained with the cuvette. However, the error of such determinations has proved to be rather high.

The use of *radioactive materials* avoids much of the tediousness of the original dye procedure and permits repeated successive determinations of cardiac output and residual volume of blood in the right ventricle. Pritchard et al. have used tracer doses of I^{131} adsorbed on human serum albumin. The radioactivity of the arterial blood concentration can be measured by a *scintillation counter* as the blood flows over the counter, and the dilution curve is continuously recorded by means of a Berkeley count-rate computer. In dogs, the application of this procedure with values simultaneously determined by an optically recording flowmeter agree within 9 per cent if allowance is made for the unmeasured coronary flow in the *rotameter* values. In the human being, the method, as compared with cardiac catheterization in a group of 12 patients, showed a variation of -8.4 to $+18.7$ per cent with a general average of ± 8.3 per cent.

The use of *radiopotassium* (K^{42}) as the test substance minimizes the errors due to recirculation and its rapid disappearance permits repeated measurements at intervals of 5 min or less. In dogs, excellent agreement is reported between this and the Fick procedures (Conn and Goldberg).

The laborious calculation of the cardiac output from the concentration curves may also be simplified by an empirical procedure which does not greatly increase the inherent variability of the procedure (Warner and Wood).

The cardiac output may also be determined by a constant infusion technique employing *p*-aminohippuric acid (Sapirstein et al.). During a constant infusion of this substance, its plasma content rises. The time–plasma-concentration curve on discontinuing the infusion may be used to calculate the cardiac output and the values obtained agree with those obtained by the dye-dilution technique in subjects who show no obvious disturbance in fluid balance.

Physical Methods. A number of physical methods have been suggested for determining the cardiac output but none has proved sufficiently accurate to be of practical value. The advantage of such procedures would reside not only in their relative ease of performance but also in the fact that their use would allow the determination of the stroke volume rather

put in some individuals undergoes a cyclic change with the menstrual cycle. To what extent this is an indirect result of emotional disturbance is not established.

Psychic Disturbance. *Psychic disturbances are potent factors which markedly increase the cardiac output.*

Temperature. There is an increase in cardiac output as the environmental temperature exceeds 25°C. Between 0 and 25°C, the cardiac output remains relatively constant since the decrease induced by peripheral vasoconstriction is compensated for by *an increase due to shivering and increased tone* of the *musculature* On the other hand, in an environment above 25°C, there is an increase in cardiac output which may amount to several liters, reflecting the increased blood flow through the dilated peripheral vessels and the increased metabolism induced by the elevated temperature.

Exercise. Muscular exercise markedly increases the cardiac output. The magnitude of this increase depends upon the severity and type of exercise On the other hand, the increase in cardiac output is not proportional to the amount of work performed, but depends *rather on the nature and the efficiency with* which it is performed.

Oxygen Content of Inspired Air. There is a rapid increase in cardiac output when the oxygen tension of the inspired gas is less than 100 mm Hg. At an oxygen tension of 60 mm Hg, *the cardiac output* is more than double the basal value. On the *other hand, increasing the* oxygen tension of the inspired air above 100 mm Hg does not affect the cardiac output If the oxygen tension changes over a prolonged period, for example, on ascent to a high altitude, *the cardiac output gradually rises* Thus, at Pikes Peak (*altitude 14,109 ft, 4,300 m*) where the average barometric *pressure is* 450 mm Hg corresponding to an oxygen tension of 95 mm Hg, as compared to 160 mm Hg at sea level, Grollman observed a gradual increase *in* cardiac output which reached its maximum on about *the fourth* day, after which it declined gradually, *reaching its previous* normal level on about the seventh or eighth day, corresponding to the time at which the hemoglobin had increased to its new level The increase in cardiac output may thus be looked upon as a temporary *compensation* for the reduced oxygen content of *the arterial blood* which is *ultimately compensated for* by an increase in *the oxygen-carrying* capacity of the blood.

PHARMACOLOGICAL STUDIES

Cardiac output determinations have been made on the human being after the administration of various therapeutic agents. The *results* of such studies often differ *considerably from* those based *on studies made on isolated* organs or on anesthetized animals. However, one must remember that the observed changes may be an indirect result of the drug. Thus, *alcohol* in small doses (30 ml) in the normal subject habituated to its ingestion results in no demonstrable effect on the cardiac output. In the teetotaler, on the other hand, an increase is *often observed secondary to the psychic disturbance* induced by its ingestion Likewise, in therapeutic doses, *caffeine* induces changes in cardiac output which differ in different individuals, tending to increase the cardiac output in those whom the drug stimulates, and to have lesser effects on those inured to its action. Likewise, following the use of *tobacco,* little effect *is observed in* those who are *chronic smokers,* whereas the *tyro is more* apt to show an increase in cardiac output, probably secondary to the side effects of this drug

Carbon Dioxide. The inhalation of carbon dioxide is without effect on the cardiac output until a concentration of 6 per cent in the *inspired air is reached.* This or greater concentrations markedly *increase* the cardiac *output* about 30 to 40 per cent above the basal value.

Digitalis. Digitalis, because of its great clinical importance, has been widely studied for its effects on cardiac output. In normal individuals, digitalis decreases the cardiac output, thus *accounting for the deleterious action* which this drug exerts *in such individuals* On the other hand, in the patient with cardiac *dilatation*, digitalis increases the cardiac output, an effect which is in accord with its beneficial action in disease.

Sympatheticomimetic Agents. The sympatheticomimetic drugs, such as *epinephrine,* markedly increase the *cardiac output,* as is to be anticipated. Similar results have been obtained with other agents of this type, e.g., *sympathin, tyramine,* or *ephedrine.*

on Pikes Peak. The procedure was elaborated by Starr, who appreciated the fact that the ballistocardiogram is related chiefly to cardiac force. The latter is related to the acceleration of the blood, whereas the cardiac output is related to its displacement.

Were the ballistocardiogram a true record of force, its second integral might be related to the cardiac output. However, estimates of the cardiac output by formal integration of the ballistocardiogram have proved inaccurate. Since force curves differ widely in relation to stroke volume, calculation of the cardiac output from the ballistocardiogram remains an empirical procedure and marked discrepancies exist between the results obtained by its use with those obtained by other methods. At present, no clear directions can be given for estimating the stroke volume from the ballistocardiogram (Starr).

PHYSIOLOGICAL VARIATIONS

The earliest applications of cardiac output studies were in determining the changes which this function undergoes under normal physiological variations As was to be anticipated, it was found that the cardiac output underwent marked changes and rapid adjustments under different physiological conditions, in order to meet the variable demands of the cardiovascular system.

Daily Variations. Because of the errors inherent in the earlier methods used for determining the cardiac output, marked variations were obtained in normal subjects in apparently constant basal conditions from day to day. With the perfection of these methods, however, it could be demonstrated that the cardiac output varied little under fixed basal conditions in any given individual and in fact could be predicted for normal individuals on the basis of their surface area. This led to the use of the cardiac index to designate the cardiac output per unit (square meter) of surface area. The fact that the cardiac output is constant from day to day allows one to draw conclusions regarding changes in this function occurring as a result of therapeutic procedures or such physiological changes, as those caused by residence at high altitudes, which occur progressively over a period of days. The concept of a normal cardiac index also permits one to predict the normal value for a given individual and thus to evaluate the deviation of a given observation from the normal.

Age. As might be predicted, the cardiac output and cardiac index tend to decrease with age, reflecting the more active metabolism and better vascularization of the young as compared to the aged.

Position. The determination of the effect of position on the cardiac output has led to widely divergent results. The excessively great cardiac outputs observed by earlier procedures, using indirect respiratory methods in the recumbent as compared to the sitting and standing positions, were undoubtedly a result of errors in the determinations, which were exaggerated in the recumbent position. However, it would appear that there is a moderate decrease in cardiac output as one changes from the recumbent to the sitting and from the sitting to the standing positions.

Food and Fluids. The increase in cardiac output induced by the ingestion of food has been demonstrated repeatedly. The magnitude of this rise varies from 0.5 to 2.0 liters in different individuals depending upon various factors, chiefly the size and composition of the meal. Since the rise in cardiac output is abrupt, it is initially, in part at least, reflex in origin rather than a result of local action in the digestive tract. The ingestion of a large volume (1 liter) of water also results in an increase in cardiac output of approximately a liter which is evident within 30 min and continues for about 1½ to 2 hr. On the other hand, the ingestion of an equal quantity of isotonic saline solution results in a lesser but more prolonged increase in cardiac output.

Sleep. Sleep, as contrasted to the waking state at the same hour and under the same conditions of physical rest, is not characterized by any appreciable diminution in the magnitude of the cardiac output. However, there is a gradual decline in the cardiac output during the course of sleep which decreases to a subbasal value reached during the early morning hours. This decrease is comparable to that observed in the oxygen consumption, arterial blood pressure, and pulse rate.

Menstrual Cycle. Determination of the effects of the menstrual cycle on the cardiac output have led to diverse results. In certain individuals, no definite pattern is observed, but it has been claimed that the cardiac out-

In patients whose failure is of recent origin and in whom the myocardium is relatively uninjured by the disease process, as in systemic hypertension or aortic valvular lesions, the cardiac output is usually within normal limits

diac output is also observed in combined fauure in such conditions as arteriovenous fistulas, beriberi, thyrotoxicosis, and severe anemia, disturbances which produce a high cardiac output prior to decompensation In these conditions there is a fall in cardiac output with the onset of congestive failure, but the cardiac output may still remain above normal even in the presence of cardiac failure.

One may generalize by saying that the failing heart is characterized by a cardiac output which is lower than it was prior to the onset of failure, although the actual level may lie in a normal range or be somewhat elevated. A more specific characteristic of the failing heart is its incapacity to increase the cardiac output adequately on exertion. The failing heart responds to digitalization by an increase in cardiac output and a fall in the diastolic ventricular pressure. When heart failure has subsided, the hemodynamic pattern turns toward normal and the cardiac output approaches the prefailure level, although it may not reach normal values. In some patients who have recovered from failure and whose myocardium is severely damaged, exercise may fail to cause as great a rise in cardiac output for a given increase in total oxygen consumption as it does in the normal individual It is very probable that in the early stages of heart failure the stroke output fails to rise despite a rise in ventricular diastolic pressure (Ferrer and Harvey)

Rheumatic Heart Disease. In patients with rheumatic mitral stenosis, the cardiac output may be low, but in some there is a normal resting cardiac output. However, there is no increase or an inadequate increase on exertion Following commissurotomy, the resting level of cardiac output may remain unaltered, but the capacity of the heart to increase the cardiac output on exertion may return to normal In patients with nonvalvular degenerative forms of myocardial disease, even in the absence of any symptoms referable to congestive heart failure, the resting cardiac output is almost invariably reduced (Ferrer and Harvey).

Arrhythmias. In general, arrhythmias of a nature which result in incapacitation or in interference with the normal activities of the individual are accompanied by a decreased cardiac output. In patients with atrial fibrillation or flutter in congestive failure, the cardiac output and the stroke output are almost always markedly reduced.

Disorders of the Thyroid. In hypo- and hyperthyroidism the alteration in cardiac output is roughly proportional to the changes in metabolism.

Pericardial Affection. In affections of the pericardium, such as concretio cordis, failure is accompanied by a marked decrease in cardiac output.

Hypertension. The cardiac output in essential hypertension is normal in the earlier stages of this disease This indicates that the underlying abnormality is an increase in peripheral resistance. The normal cardiac output in hypertensive cardiovascular disease differentiates this disorder from the elevation in blood pressure seen in other conditions which are accompanied by an increase in cardiac output.

Anemia. In conditions characterized by a decreased oxygen-carrying capacity of the blood, as in anemia, the increased cardiac output compensates for the deficiency. When the hemoglobin falls below 7 Gm, the resting cardiac output increases, rising sharply as the hemoglobin is reduced below a critical value of 4 Gm/100 ml.

RELATION OF CARDIAC OUTPUT TO RENAL BLOOD FLOW

In a study of 146 patients suffering from various forms of heart disease, Werko et al., utilizing the direct Fick principle, noted no definite trend in the relationship of the cardiac output to the renal blood flow The latter was lower than normal in all patients with cardiovascular disease and was roughly proportional to the severity of the heart disease. Depression of the cardiac output was usually associated with a marked degree of pulmonary hypertension The association of a low cardiac output with a decreased renal blood flow is understandable However, the renal plasma

Vasodepressor Agents. Unlike their action in the anesthetized animal, moderate doses of vasodepressor substances, such as *histamine*, *acetylcholine*, or the *nitrites*, exert no effect on the blood pressure of the normal human being, but increase the cardiac output, which thus maintains a normal blood pressure level. Only when the dose administered is large does the administration of these agents result in a decrease in cardiac output.

Hormones. Insulin, injected in a dose sufficient to produce *hypoglycemia*, markedly increases the cardiac output. Other drugs which induce hypoglycemia induce a comparable increase which reflects the well-known cardiac-stimulating and -accelerating effects of a lowered blood sugar content.

Pituitrin increases the cardiac output as does its Pitressin component. On the other hand, the Pitocin fraction of pituitrin has little effect on the cardiac output.

PHYSICAL THERAPEUTIC MEASURES

The effect of various therapeutic measures on the cardiac output varies. Thus, massage and passive movements of the muscles, although increasing the oxygen consumption, do not affect the cardiac output appreciably. Baths, on the other hand, affect the cardiac output to a variable degree depending upon the temperature of the water and its gaseous content. Irradiation of the skin by ultraviolet light also increases the cardiac output by as much as 30 per cent.

CLINICAL APPLICATIONS

Although furnishing only an indirect estimate of the force of systolic contraction, the cardiac output serves as the only available and consistent estimate of this function. Since *neither the work done by the heart nor its* mechanical efficiency can be accurately determined in man, the cardiac output serves as the best criterion of these functions. Failure of the cardiac muscle thus has been defined as existing when despite a rise in ventricular filling or diastolic pressure, there is no longer a corresponding rise in the stroke output which may remain at prefailure levels or decline (Ferrer and Harvey).

Heart Failure. The most commonly encountered failure in patients with hypertensive, arteriosclerotic, or aortic valvular disease is *left ventricular failure*, which results in an increase in diastolic residual blood volume, a rise in diastolic pressure and a decrease in cardiac output. In left ventricular congestive failure, the cardiac output, although lower than before the onset of failure, may, however, still be in a normal range. In patients with intrinsic myocardial damage, such as occurs in coronary artery and rheumatic heart diseases, the cardiac output is markedly reduced. In patients with the so-called hypodynamic heart, the resting cardiac output is also low although no congestion is noted clinically.

In patients with *congestive failure*, the cardiac output, if normal or at the lower limits of normal, fails to increase on mild exercise, reflecting the incapacity of the myocardium to respond to the demands of exertion by augmenting its output.

In patients with isolated *right ventricular failure*, as encountered in *cor pulmonale*, the hypoxia resulting from respiratory dysfunction may cause an increase in cardiac output. The augmentation of blood volume in these patients also increases the diastolic right ventricular volume, therefore producing an increased stroke output which is present prior to the onset of heart failure. When the right ventricle fails, there is a fall in systolic output, and although the cardiac output may now decline from its previously high level, it may still remain higher than normal. This introduces the paradox of a high cardiac output in the presence of failure. The ventricles in this form of heart disease are able to sustain a high cardiac output not only before failure but even in its presence (Cournand and Richards).

Digitalization relieves right ventricular failure by inducing a more adequate emptying of the ventricle with a rise in cardiac output. When pulmonary insufficiency is corrected in the patient with chronic cor pulmonale, disturbances secondary to this are removed and the high cardiac output returns toward normal.

In *combined left and right ventricular failure*, the resting cardiac output may be either low, normal, or high. In conditions in which there is an intrinsic myocardial lesion, as in coronary artery disease and in certain patients with rheumatic myocarditis, the cardiac output is almost always reduced and seldom brought to normal even under digitalization.

In patients whose failure *is of recent origin* and in whom the myocardium is relatively uninjured by the disease process, as in systemic *hypertension or aortic* valvular lesions, the cardiac output *is usually within* normal limits [illegible]

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flow was often reduced in patients with a normal cardiac output. In some of these patients the stroke volume was low although the cardiac output was normal. Hence, there was a better correlation between the reduced stroke output and the renal blood flow. In patients with severe heart disease with increased pressures in the pulmonary circulation and decreased cardiac output, the renal blood flow was always greatly reduced regardless of whether the patient had signs of right heart failure or not.

DETERMINATION OF BLOOD VOLUME

Studies on cell, plasma, and blood volumes form an extensive literature. The earliest, so-called *direct methods* involved the collection of blood from dead persons (Welcher, 1854). The *indirect methods* are applied to living persons The basic principle is to introduce *a test substance* into the blood circulation and, after mixing, to determine the dilution, then the blood volume is calculated. Attempts have been made to find indicators that are not eliminated before mixing in the blood stream, and the concentration of which is easily measurable. Thus, by using substances that are distributed in the plasma, a proper determination of *plasma volume* is rendered possible. Further, by introducing labeled erythrocytes into the blood stream, the *red cell volume* can be estimated. From these primarily determined values of plasma and cell volumes, the *total blood volume* is calculated through the use of the venous hematocrit, or it could be calculated as the sum of total red cell volume, separately determined. Lastly, the amount of *hemoglobin in the body* is estimated by letting a definite quantity of carbon monoxide combine with the hemoglobin, and thereafter determining the carboxyhemoglobin concentration The total blood volume is calculated from the common hemoglobin value

Injection of different *dyes* into the circulation has been used for determination of the plasma volume The *dye method* was introduced by Keith et al (1915) Dawson et al (1920), in a comprehensive investigation of 60 different dyes, found that *the azo dye Evans blue (T 1824)* was the best available for these tracings Evans blue, which is easily soluble in water, has been shown to combine with the serum albumins (Rawson). It is eliminated through the capillary wall either in combination with albumin (Rawson) or in the free state (Le Veen et al.), it appears in the lymph about 20 min after the injection, increasing in concentration with time (Cardozo and others). Not more than 2 per cent will return to the blood within 1 hr (Ferrebee et al.). Many investigations deal with the problem of the disappearance of the dye in various clinical conditions.

Concentration curves obtained from an artery after intravenous injection of Evans blue illustrate two processes: the mixing of the dye in the circulation and its disappearance from the circulation. Since these two processes can take place simultaneously, the curves may be difficult to interpret. Generally, the explanation of Gibson and Evans (1937) has been accepted. They maintained that the curve consists of two principal parts, a mixing curve, demonstrating the steeper fall during the first few minutes, and a disappearance curve indicative of a slower loss of dye from the circulation, due to the factors mentioned above. The point of intersection of these two segments, i.e., mixing time, denotes the time required for mixing in the circulation. This explanation has caused numerous controversies. Kennedy et al. and Cruickshank et al. maintained that the dye begins to leave the circulation during the mixing phase and is absorbed by the reticuloendothelial system. Robinow et al. were of the opinion that mixing was already established after 1 min. By injecting undyed plasma into dogs dyed with Evans blue, Lawson et al found that mixing was complete within 2 to 5 min The same length of time was required for the mixing of injected labeled cells (see below) They failed to notice an initial rapid fall in the concentration of Evans blue, in contrast to the results obtained by the methods commonly used.

Extrapolation methods have been used for interpreting the dye curves which were obtained: linear extrapolation (Gibson et al.), semilogarithmic extrapolation (Gregersen et al.), double logarithmic extrapolation to one min-

ute (Overbey et al.), and root extrapolation (King et al.). *Some investigators*, instead of using extrapolation methods for calculating the plasma volume, have based their determinations on the concentration of dye in single blood samples. *Difference in the plasma volume* has been noted when calculated from the latter method *as against linear extrapolation* (Gregersen et al).

It is most convenient to determine the Evans blue in plasma solutions by using a spectrophotometer which is read at 620 mμ (Gregersen et al.). It is sufficient to make a standard curve of different concentrations of Evans blue for each preparation of dye.

The carbon-monoxide-inhalation method was introduced by Gréhant and Quinquaud (1882). It is based on the fact that, when a known volume of carbon monoxide is supplied to the blood by inhalation, it combines with *the hemoglobin to form* carboxyhemoglobin When equilibrium has been reached, the *carboxyhemoglobin content of the blood is determined* The total hemoglobin is calculated from the quantity of carbon monoxide supplied and the *carboxyhemoglobin* concentration

The *original* method has been improved and modified several times, both as far as the inhalation apparatus, and the determination of carboxyhemoglobin *are concerned* (Haldane and Smith, van Slyke, Grosse-Brockhoff, Root et al, Sjostrand, Courtice and *Gunton*). According to *Root et al* and Sjostrand, about 2 to 3 *per cent of* carbon monoxide combines with myoglobin. Carbon *monoxide also combines with the hemoglobin* of the *bone marrow* (Gregersen and Root) In their opinion, the difference in volume of cells tagged with radioactive iron and those *combined* with carbon monoxide (Nickerson et al) is of the order of magnitude that would be *expected* from estimates of the quantity *of red marrow* An inappreciable part of the carbon monoxide is *presumably oxidized* into carbon dioxide (Tobias *et al*) An initially high carboxyhemoglobin *content, amounting* to 1 per cent or more, *is found* chiefly in smokers but, even in nonsmokers, values about 0.4 ml/100 ml are obtained (Root et al) Thus, it is necessary to estimate this initial *carboxyhemoglobin* value before the inhalation of *carbon* monoxide is started. It is assumed *that* equilibrium in the systems is attained after 15 min of inhalation. The carboxyhemoglobin value estimated *after the following* 15 min of breathing is about 3 *per cent lower* Much work dealing with different clinical problems has been performed with the carbon monoxide method.

Radioactive isotopes of iron, phosphorus, potassium, chromium, and thorium B have been used for labeling the red blood corpuscles. The labeled *cells* are injected into the blood stream and, after mixing, the radioactivity of *the erythrocytes* is determined in blood samples *Total red cell volume* of the subject is *then ascertained from the* values obtained, i e, the radioactivity and volume of injected corpuscles and the corpuscular radioactivity of drawn samples.

After they had established that *radioactive iron becomes* incorporated in the hemoglobin, and that its concentration in the erythrocytes remains constant for a long time, Hahn et al. (1941) introduced a method whereby blood containing *erythrocytes labeled with radioactive iron* from a donor dog, was injected into the test animal the total red cell volume of which was to be determined. *Gibson et al.* and Meneely et al applied the method to human beings. The radioactivity of the labeled cells is constant in the drawn samples for a considerable time, thus allowing the investigator *to carry out* different circulatory determinations, from the second minute on. However, this method requires a group *of donors who* have been charged with radioactive iron for an appreciable time. Furthermore, subjects *with* different blood groups require different donors These donors are exposed to radiation emitted by Fe^{59} *for an* appreciable *time*, as the radioactive iron is almost quantitatively conserved in the organism and disappears *only through* radioactive decay, which takes place over a half life of 47 days Thus, the practical applicability of this labeling method is limited, and other isotopes are used for circulatory studies

On the basis of several *studies* concerning *the uptake of radioactive phosphorus in* blood *corpuscles*, Hevesy et al. presented a *method* for *determination* of *total red cell volume*, whereby the red cells of the subject (*rabbits*) were labeled in vitro. The activation of the blood corpuscles *is due* to an exchange between the inorganic *phosphate* of the plasma and that of the corpuscles *and by an incorporation* of inorganic *cell* phosphate into acid-

soluble organic phosphorus compounds. The fact that phosphate penetrates fairly slowly into the erythrocytes but is rapidly incorporated into labile acid-soluble compounds has the effect of appreciably enlarging the pool available to the phosphate. The radioactive phosphate is distributed not only among the inorganic phosphate ions present in the corpuscles but also among the labile acid-soluble organic molecules present. Thus, the rate of elimination of radioactive phosphorus into inactive plasma is very much slower than it would be without such a distribution.

It has been shown that the permeability of the erythrocytes to phosphate is considerably increased at 37.5°C. The blood is thus activated by leaving it in a bottle to rotate for 1 to 2 hr in a water bath at 37°C. After incubation, either the whole labeled blood or the washed labeled corpuscles are injected into the blood stream. The loss of the corpuscular radioactivity, when washed cells are injected has been calculated to be 5 per cent within 30 min and 6 to 9 per cent within 1 hr. When whole labeled blood is injected, it has been shown that the loss and uptake of P^{32} by the corpuscles balance each other. Thus, the total radioactivity of the circulating corpuscles is not notably changed in the course of a time interval of 0 to 60 min. Extrapolation is not required when injections of labeled whole blood are used. However, by injecting washed labeled corpuscles, the radioactivity can be measured on whole blood hemolyzed with saponin without separating corpuscles and plasma. Both techniques are used.

Phosphorus-32 decays in a half life of 14.3 days and emits a rather strong β radiation, which is easily measured by a common Geiger-Muller counter. It has been widely used for circulatory investigations.

In recent years, other isotopes have been used for the labeling of red corpuscles. Thus, Hevesy and Nylin, as well as Yalow and Berson have used K^{42}-labeled corpuscles in red cell volume determinations. After labeling the erythrocytes in vitro at 37°C for 2 hr, the blood sample was injected into the subject. In the course of one hour, within the error of measurements, no change in the radioactivity of the red corpuscles could be observed when whole labeled blood was injected. Labeled washed red cells injected into the circulation lost on an average 3.5 per cent of their K^{42} content in the course of the first hour.

In 1950, a method for determination of the total red cell volume in man by using *radioactive chromium* was introduced by Sterling and Gray. Chromium-51, which disintegrates by potassium capture and emission of soft x-rays and gamma rays, has a half life of 26.5 days. A study of the kinetics of the uptake of sodium chromate by red cells indicated that the anionic sodium chromate diffused through the cell membrane and was then firmly bound by the hemoglobin, particularly by the globin fraction, probably after reduction to the cationic trivalent state within the red cells. This marked affinity of the erythrocytes for the anionic chromate ion is demonstrated by the rapid uptake of radioactive chromium following the addition of sodium chromate to either saline solution suspensions of washed red cells or to whole blood. Eighty to ninety per cent of the isotope was found to be bound to the red cells within 2 hr. Washed red cells, tagged with sodium chromate and injected into a human being, retain their radioactivity without significant loss to the plasma for 24 hr (Gray and Sterling; Reilly et al.; Nylin and Hedlund). It must be added that the amount of chromium added to the circulation must be below the toxic level. Further, it is necessary to use a scintillation counter, so that a large percentage of the total disintegration due to the gamma ray emission is recorded. Another disadvantage is the separation and washing procedures necessary before the injection of the labeled cells into the circulation. Lastly, the patient is subjected to prolonged radiation from Cr^{51}.

Another method has been described for labeling the erythrocytes with *thorium B* (Hevesy and Nylin, Nylin and Hedlund). Powdered radioactive thorium is placed in a bottle, thoron, which emanates from the powder, is carried, in an oxygen stream which passes through it, to the blood sample from the subject to label it (Fig. 4-184). Excess thoron is absorbed in vegetable oil.

The radioactivity of the red blood cells increases with the length of the period of irradiation and the rate of flow of the oxygen. Subsequent agitation in a water bath at 37°C raises the distribution coefficient, i.e., the quotient of impulses for red cells and for plasma, to about 300. The tagging of the cells depends upon their affinity for one of the decay products, thorium B. The radioactivity of the adhering plasma can be neglected, and it is thus possible to inject the irradiated whole blood directly into a vessel, omitting the separation and washing procedures with their risk of induced hemolysis. Owing to the high distribution coefficient, samples can be prepared from whole blood for both standard and drawn samples. The measurement is a simple matter because of the rather strong beta particle emission. Washed blood corpuscles, injected into the circulation, lost (on an

average) 1.8 per cent of their activity during the first hour, while the mean loss per hour was 1 2 per cent, calculated from a decrease in the radioactivity of 29 per cent in 24 hr. When labeled whole blood was injected, the average loss was 2.3 per cent in the first hour, while the mean loss over 24 hr was 1.2 per cent/hr The observed decrease in activity after 1 and 2 hr is not statistically significant Since thorium B has a half life of 10 6 hr, the patient is exposed to only a short period of radiation, and subsequent injection of cells labeled with an isotope will not be affected by residual cell activity Besides beta radiation, the decay products of thorium B emit soft alpha and gamma rays The technique for preparing the samples is simple A pack of good-quality filter paper is clamped snugly in the bottom of a dish filter paper and absorbed, and the whole pack is then placed in a shelf drier The same technique has been used in preparing for injection washed corpuscles labeled with P^{32} The standard error of the method is $\pm 2\,0$ per cent

The isotope-labeling technique has also been used for estimation of plasma volume. Solutions of serum albumin tagged with I^{131} have been employed for this purpose (Fine and Seligman, Krieger et al, Crispell et al.), as well as radioactive chromic chloride (Gray and Sterling) Gray and Sterling found that cationic hexavalent chromic chloride is firmly bound by the plasma proteins both in vivo and in vitro When injected intravenously, 98 per cent or more of this compound is immediately bound by the plasma proteins with a minimal loss of the isotope to the red cells, in vitro tagging is thus unnecessary It is recommended that the samples be counted, while wet, in a gamma ray counter In the circulation, a relatively slow rate of disappearance of plasma protein tagged with either I^{131} or Cr^{51} has been recorded It has been suggested that a correction for the loss of protein-bound radioactive chromic chloride from the circulation can be made by extrapolating the dilution curve to zero time (Gray)

It is clear that the isotopes available for estimation of total cell volume differ in several respects from each other type of radiation, technique of incubation and of preparation for measurement, choice of counters, and lastly the rate of loss of radioactivity from the labeled cells in the circulation There are advantages and disadvantages to each isotope-labeling technique. The investigator has to choose that method which is most appropriate for his work In any case, corresponding values of the total red cell volume are obtained with all the tagging methods discussed. Berlin et al have shown in experiments on mice that there is no significant difference in the values for blood volume obtained when using radioactive phosphorus or radioactive iron. Determinations of the total cell volume in the same patient with Th^{82} and P^{32}, as well as with Th^{82} and Cr^{51}, give similar values (Nylin and Hedlund, Fig 4-185). About the same values are also obtained by using K^{42} and P^{32} (Yalow and Berson). Corresponding values of total red cell volume per kilogram body weight have been obtained with the various isotope techniques in a series of normal cases (see below). On the other hand, the total red cell volume, estimated with the dye–venous-hematocrit method, is about 13 per cent higher than that obtained with any of the isotope methods

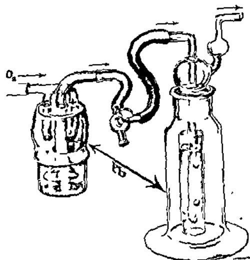


Fig 4-184. Thoron, which emanates from the powder of radioactive thorium placed in the bottle, is carried in the oxygen stream through the blood sample from the subject to activate it.

Assuming that tagging methods lead to a correct value of the cell volume and that Evans blue gives the correct value of the plasma volume, one arrives at a correct blood volume figure by adding these two data From this figure and from the value of the total red cell volume, the body hematocrit is calculated When comparing body hematocrit to venous hematocrit, a ratio of about 0 9 is found The same quotient was obtained by Gray and Sterling when they estimated the

red cell volume with radioactive sodium chromate and the plasma volume with chromic chloride. Several investigations have been performed to evaluate this difference. The results seem to be that the distribution of red cells and plasma varies from one vascular section to another and that the circulatory conditions of erythrocytes and plasma differ from one another. Accordingly, a determination of one of these components cannot bear out any definite conclusions regarding the other. In order to ascertain the total red cell volume, methods directly serving this purpose should be used, while plasma methods should be adopted for determinations of the plasma volume. Values that correspond well have been obtained by using the carbon monoxide and dye methods for determining blood volume (Root et al.; Courtice et al.; Hooper et al.), although 7 per cent lower values have been found with the carbon monoxide method (Bazett et al) and also higher values with the same method (Asmussen) These results are explained by the fact that total body hemoglobin-myoglobin is not the same as total red cell volume as cited above

The *total red cell volume* has been estimated in a large series of normal cases with the isotope-tagging method. Similar values have been obtained with different isotopes.

Radioactive iron gives a value of 29 7 ml/kg body weight (Gibson et al.) With radioactive phosphorus, the following values have been obtained: 33.3 ml/kg (Hevesy et al.), 28 9 ml (Nylin and Hedlund), 30.2 ml (Mayerson et al.), 33 9 ml (Kelly et al.), 30.4 ml (Reeve et al.), 29.2 ml (Nachman et al.), and 29.3 ml (Berlin et al.). Lastly, Sterling and Gray obtained a value of 31 8 ml/kg with radioactive chromium. As mentioned above, Th^{82} (thorium B) gives the same values as P^{32} (Nylin and Hedlund).

For *the plasma volume*, too, a survey of normal values obtained by the various methods shows rather small variations among them With radioactive chromic chloride, Sterling and Gray obtained a value of 39.3 ml/kg body weight. With albumin tagged with radioactive iodine, the values were 40 ml/kg (Storaash et al.), and 42.0 ml (Schreiber et al.). The dye methods have given about the same values: with Evans blue, 43.1 ml (Gibson and Evans), 41 7 ml (Noble and Gregersen), and 41 ml (Zissler and Schneider), with trypan red, 42 ml/kg (Wollheim) Many other investigators give about the same values as those cited.

The figures for *whole blood volume* show

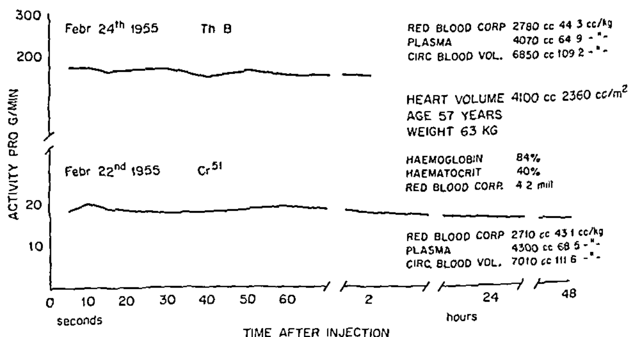


Fig. 4-185. In this case blood volume determinations were made by the Th^{82}- and Cr^{51}-labeling methods at an interval of 2 days. The agreement between the values obtained by the two procedures is close There was no significant reduction in the red cell radioactivity in the drawn samples even 2 hr after injection of Th^{82}-labeled whole blood. After injection of washed Cr^{51}-labeled cells a nonsignificant reduction of only 3 1 per cent over 24 hr was observed.

somewhat greater variation, partly depending upon the method employed, i.e., if the cell [illegible] is primarily determined, or the plasma [illegible]

[illegible] and plasma volumes. The values vary between 71 and 83 ml/kg body weight.

THE CLINICAL APPLICABILITY OF THE DIFFERENT METHODS FOR BLOOD VOLUME DETERMINATIONS

With the aid of cell and plasma volume estimations, many clinical problems have been elucidated. First to be mentioned are clinical and experimental investigations concerning changes of blood volume caused by different physical and pharmacological agents

An increase in plasma volume, caused by heat, muscular exercise, and epinephrine injections has been observed by many investigators, all using the dye methods. The conclusion was that certain organs and parts of the venous system should be considered as *blood depots* However, this was not confirmed *by the isotope-tagging methods* It was then suggested that exercise and epinephrine cause a *redistribution* of red cells and plasma resulting in a rise of the venous hematocrit, without any increase in the volume of red cells and plasma.

Dilution curves of normal subjects, with P^{32}- or Th^{82}-tagged *erythrocytes*, were plotted from samples drawn from the *brachial artery* after intravenous injection of the labeled cells and showed that the maximum peak appeared within 15 sec and the recirculation within 20 sec A steady level was observed after 1 to 2 min

A more rapid *mixing within the heart* was found in the standing than in the recumbent position (smaller heart when standing), while the final mixing of the labeled red cells with the subject's blood was delayed (retarded circulation in the lower extremities when standing)

In cases where surgical *operations* were performed under anesthesia, delayed mixing and a statistically significant decrease in the corpuscular activity were found Spinal anesthesia alone does *not* cause a significant decrease in the activity of the *red cells* An extreme retardation in mixing was observed under anesthesia (Nylin et al) Since neither the erythrocyte volume nor *the whole blood volume* was *decreased*, it is *apparent* that there was a slower blood flow in the small arteries or capillaries. An additional loss of plasma through the capillary wall into the tissues could not be shown by Fine and Seligman with plasma proteins labeled with S^{35} and I^{131}. Only in a traumatized region, as in large burns, are the capillaries more permeable. Using Fe^{59}-tagged erythrocytes, Hahn et al. found that *in hemorrhagic shock* there *was an instantaneous compensation* for the lost blood by an increase of plasma.

The total red cell volume is increased in *polycythemia vera*. This represents a difference from relative polycythemia which is important, because the venous hematocrit fails to give any clue to the diagnosis

In *congestive heart failure*, there is a slight polycythemic reaction due to the increased erythropoietic activity, both the total red cell volume and the plasma volume are increased. When compensation occurs, the erythropoietic activity decreases and the total red cell volume becomes normal. The plasma volume, as well as the total blood volume, decreases. The reactive polycythemic reaction can be pronounced in certain congenital heart diseases, such as the tetralogy of Fallot (Nylin et al.). The total red cell volume decreased after surgery of this condition (Fig 4-186).

The total red cell volume is decreased in *hypochromic* and *pernicious anemias* and in *pulmonary tuberculosis*

With the aid of Fe^{59}-labeled erythrocytes, Caton et al have established that there is a successive increase in red cell volume during *pregnancy* with a maximum value at delivery, and that the red cell volume returns to normal values about 60 days after delivery. The rise in *total hemoglobin during* pregnancy was shown by Sjostrand et al. with *the carbon* monoxide method.

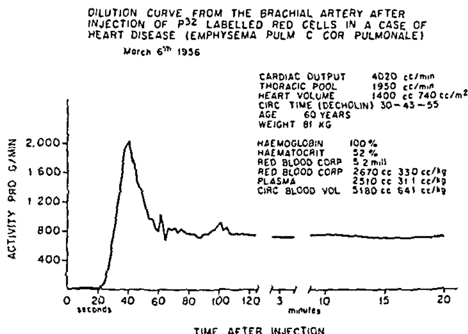
From dilution curves obtained from the brachial artery after intravenous injection of labeled red cells (Nylin et al) or Evans blue (*Hamilton et al*; Cournand et al; Lagerlof et al.) it is *possible to calculate cardiac output*.

From the values of *the cardiac* output and the mean circulation time, the *thoracic pool volume* can be calculated. It amounts to about 1 5 liters/m² of body surface (Hamilton et al.; Nylin and Hedlund). When injecting into the

pulmonary artery, the pool volume is of course lower, values of about 800 ml/m² being obtained (Ebert et al.; Lagerlöf et al.; Rappaport et al.).

The thoracic pool volume increases in cases of mitral stenosis, as well as in cases of coronary artery disease and hypertension (Kopelman et al.; Nylin and Hedlund). There is good correlation between the heart volume and the thoracic pool; i.e., the pool volume increases with the heart volume, a fact which is explained by the augmented residual blood volume of the heart. The pool volume reaches extremely high values in subjects with large hearts. After digitalization, both the pool volume and the total blood volume decrease, while cardiac output increases.

With the aid of labeled erythrocytes, it has



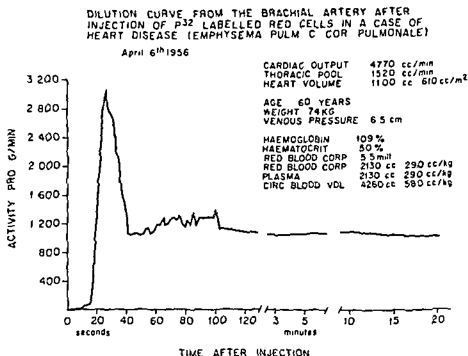


Fig. 4-186. These dilution curves were obtained from a patient with congestive heart failure, before and after treatment. When compensation occurred the total blood volume, total red cell volume, and thoracic pool volume decreased with the heart volume. The decrease in the thoracic pool volume depends above all on the diminishing volume of residual blood in the heart.

been possible to calculate *cerebral blood flow* (Nylin et al.). *Blood samples* are drawn simultaneously from the two jugular bulbs after injection of the tagged red cells into the carotid arteries. The cerebral blood flow is calculated as about 1.0 liter/min. It is also possible to calculate the *cerebral blood-pool volume,* which is about 130 ml (Fig. 4-187). *The turnover of* the cerebral pool is about eight, that is, the cerebral blood volume is replaced eight times a minute. In comparison, the turnover of the thoracic pool was found to be only *one-half* this value. The cerebral pool volume amounted to only 3 per cent of the total blood volume.

ROENTGENOGRAPHIC HEART VOLUME DETERMINATION

It is obviously very difficult to determine the volume of the heart since mathematically this organ is rather undetermined. Any method of determining this volume in a living person must be approximate and, for practical reasons, it is essential that it be as simple as possible. By using roentgenographic methods it is possible to get full data about the shape of the heart and, by using a sufficiently large number of projections, it is in principle possible to determine its volume with satisfactory accuracy.

Clinically, it is not practical to use x-ray methods using more than two projection planes. Several authors proved that the heart of a living person is a convex body and has approximately the shape of an *ellipsoid.* By assuming this information to be correct, it is possible to arrive at practical methods of de-

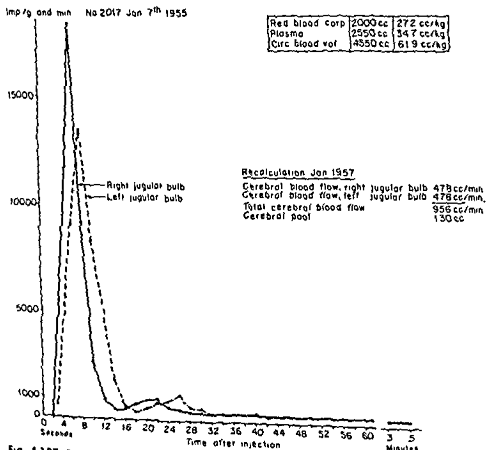


Fig. 4-187. Fairly similar dilution curves are obtained from both jugular bulbs after injection of Th[illegible]-labeled red cells into one carotid *artery of a normal subject.* Assuming symmetry of the drainage of the cerebral blood, *the cerebral* blood flow is calculated as 960 ml per minute. Neglecting the contribution to the cerebral pool from the basilar artery, the *pool volume* is estimated to be 130 ml

pulmonary artery, the pool volume is of course lower, values of about 800 ml/m² being obtained (Ebert et al.; Lagerlöf et al.; Rappaport et al.).

The thoracic pool volume increases in cases of mitral stenosis, as well as in cases of coronary artery disease and hypertension (Kopelman et al.; Nylin and Hedlund). There is good correlation between the heart volume and the thoracic pool; i.e., the pool volume increases with the heart volume, a fact which is explained by the augmented residual blood volume of the heart. The pool volume reaches extremely high values in subjects with large hearts. *After digitalization*, both the pool volume and the total blood volume decrease, while cardiac output *increases*.

With the aid of labeled erythrocytes, it has

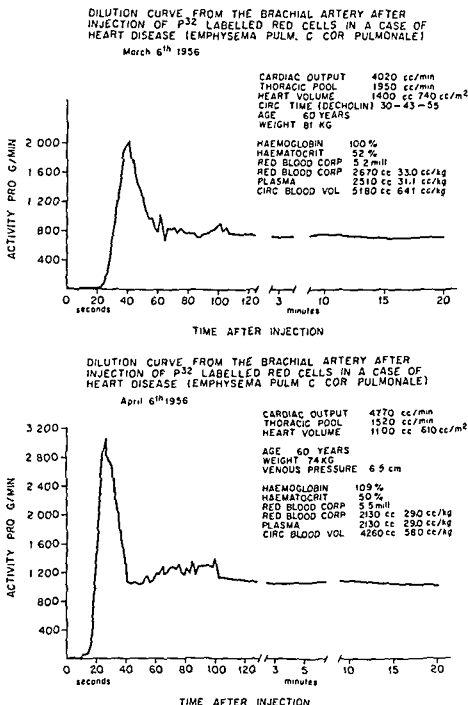


Fig. 4-186. These dilution curves were obtained from a patient with congestive heart failure, before and after treatment. When compensation occurred the total blood volume, total red cell volume, and thoracic pool volume decreased with the heart volume. The decrease in the thoracic pool volume depends above all on the diminishing volume of residual blood in the heart.

2.7 per cent ±1.1 per cent, the standard deviation being 7.4 per cent.

It can therefore be said that the modified Kahlstorf formula determines the heart volume very accurately for a biological method. In the following review the author's experience on the clinical applicability of roentgenographic heart volume determination is based on the modification of the ellipsoid formula.

PHYSIOLOGICAL HEART VOLUME CHANGES

With the author's method for biplane radiography of the heart and determination of heart volume (modification of Kahlstorf's formula), several studies have been made in different countries, especially in Sweden, of heart volume changes both in physiological and pathological conditions. It is a well-known fact that the heart decreases in size during systolic contraction, but there are different opinions as to how much it decreases With the modern seriograph film changer in the two projections, the author has studied these changes in normal persons (Fig 4-190)

The heart contour changes with *respiration*, probably on account of cardiac displacement, plus different filling of the right and the left hearts As a result of changes of intrathoracic pressure, the heart volume decreases in *pneumothorax*. One important source of error is represented by postural changes in heart volume. During *muscular exercise*, the heart also changes its volume but there are different opinions as to the extent of this variation. *Athletes' hearts* seem to be enlarged. In *obesity* the same thing happens, and this is also the case in pregnancy.

Even in physiological conditions the residual blood in the heart probably plays an important role. Presumably man needs a certain volume of residual blood in his heart to be able to accommodate himself to changes of intrathoracic pressure, postural changes, and muscular exercise.

The personal error of the investigator was studied by Axén, Lindgren, and Malmstrom (1946). In their opinion, it is exceedingly small for a biological method

NORMAL VALUES OF HEART VOLUME IN MAN

Every biological value undergoes wide normal variations The first normal values of the roentgenographic heart volume were given by Kahlstorf (1932), and were based on inadequate material (70 men and 50 women). More comprehensive investigations were made by Lysholm et al (1934), Liljestrand et al. (1939), and Biorck (1944), all using the same method of biplane teleoroentgenography. Later on,

Person	Measures in picture scale						V. cc in picture scale			V. cc in real scale		
	d_1	d_2	d_3	h	A_f	A	1	2	3	1	2	3
A S	17	14	12 5	12 3	172.3	126 0	1435	1555	1500	1150	1240	1210
M L	14	12	9 5	13 7	135 5	102.8	858	835	864	690	670	690
O P												
before treatment	17.5	15	15 5	13.5	187.5	160.3	1940	2140	1890	1560	1720	1520
after "	16	13	12.5	13 0	159 2	130.2	1330	1360	1355	1070	1090	1090

1. $V = \frac{2}{3} A_f d_3$ (Kahlstorf's primary ellipsoid formula)

2. $V = \frac{\pi}{6} d_1 d_2 d_3$ (Jonsell's formula)

3. $V = \frac{8}{3\pi} \frac{A_f A}{h}$ (B. Andersson's formula based on planimetrically determined frontal and sagittal surface when the heart is approximated to an ellipsoid)

Fig 4-189. Heart volume determinations calculated by using the three formulas.

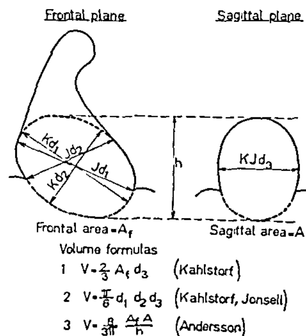


Fig. 4-188. Heart volume determination by biplane roentgenography.

termining the volume of the heart by using two orthogonal projections: one frontal, the other sagittal and parallel to the spinal column (Fig 4-188).

If the heart is an ellipsoid with two symmetrical planes parallel to those of the projections, the following formulas can be used for determination of its volume

$$V = \tfrac{2}{3}A_f d_3 \quad (1)$$

$$V = \pi/6\, d_1 d_2 d_3 \quad (2)$$

where A_f = the frontal area of the heart
d_1, d_2 = length of the principal axes of A_f
d_3 = depth of the heart orthogonal (sagittal) to the frontal plane

Even if one uses these formulas when the projection planes are not symmetrical planes of the ellipsoid, one still obtains an approximate volume $V' > V$, as proved by Andersson In actual patients, the difference between V' and V is at most 2 to 3 per cent of the volume of V Rohrer and Kahlstorf suggested that the factor 2/3 in formula (1) be replaced by 0 63. Benedetti and Bollini, and later on Poppi, Lysholm, and Nylin and coworkers, suggested different formulas for the measurement of heart volume That suggested by the author is derived from studies of Kahlstorf (1932)

Jonsell (1939) stated that the volume of the heart could be determined by formula (2) if d_1, d_2, and d_3 were defined in the following way

d_1 = long diameter taken from the junction between aorta and right atrium on the right to the left lower pole of the heart
d_2 = broad diameter from the right basal border of the cardiac silhouette to the junction between pulmonary conus and left ventricle (this may be difficult to measure in some cases)
d_3 = depth of the heart, orthogonal (sagittal) to the frontal plane
and d_1 and d_2 are supposed to be parallel to the frontal projection plane

This modified formula gives a satisfactory approximation of an ellipsoid in normal subjects. In all these methods one uses more data concerning the frontal projection than the sagittal projection, in which one only determines the depth of the heart.

It seems desirable to complete these formulas by another in which are used equivalent data from the two projections:

$$V = \frac{8}{3\pi}\frac{A_f A}{h} \quad (3)$$

where A_f = the area of the frontal projection
A = the area of the transverse projection
h = the common height of the two projections

This formula is exact if the heart is an ellipsoid with two symmetrical planes; in this case the calculated volume $V'' > V$. However, it can be shown by complex geometrical methods that the error is smaller than that resulting from the use of formula (1). The areas A_f and A can easily be determined by using a planimeter.

The volumes of some hearts were determined by this method and the results are compared in the following chart (Fig 4-189). It is impossible to say that one result is better than another but it is clear that formula (3) uses more data from the x-ray pictures than the others. In the future, more thorough comparison will be necessary.

A comparison between the heart volume determined at post mortem and the displacement of the heart, taken out after ligation of all vessels, was made by Nylin (1939) and, on a bigger scale, by Friedman (1950) and Lind (1950). Friedman found in 28 cases that the volume of the heart determined by x-ray studies during life was much larger than that determined in the same position of the body post mortem, with a mean difference of 32 per cent Thereafter, the volume of the removed heart was determined by displacement. The agreement seemed surprisingly good and the mean difference found in this series of 45 cases was

2.7 per cent ±1.1 per cent, the standard deviation being 7.4 per cent.

It can therefore be said that the modified Kahlstorf formula determines the heart volume very accurately for a *biological method*. In the following review the author's experience on the clinical applicability of roentgenographic heart volume determination is based on the modification of the ellipsoid formula.

PHYSIOLOGICAL HEART VOLUME CHANGES

With the author's method for biplane radiography of the heart and determination of heart volume (modification of Kahlstorf's formula), *several studies have been made in different countries*, especially in Sweden, of heart volume changes both in physiological and pathological conditions. It is a well-known fact that the heart decreases in size during systolic contraction, but there are different opinions as to how much it decreases With the modern seriograph film changer in the two projections, the author has studied these changes in normal persons (Fig 4-190)

The heart contour changes with *respiration*, probably on account of cardiac displacement, plus different filling of the right and the left hearts As a result of changes of intrathoracic pressure, the heart volume decreases in *pneumothorax*. One important source of error is represented by postural changes in heart volume During *muscular exercise*, the heart *also* changes its volume but there are different *opinions as to the extent* of this variation. *Athletes' hearts* seem to be enlarged. In *obesity* the same thing happens, and this is also the case in pregnancy.

Even in physiological conditions the residual blood in the heart probably plays an *important* role. Presumably man needs a certain volume of residual blood in his heart to be able to accommodate himself to changes of intrathoracic pressure, postural changes, and muscular exercise.

The personal error of the investigator was *studied by Axén, Lindgren, and Malmstrom* (1946). In their opinion, it is exceedingly small for a biological method.

NORMAL VALUES OF HEART VOLUME IN MAN

Every biological value undergoes wide normal variations The first normal values of the roentgenographic heart volume were given by Kahlstorf (1932), and were based on madequate material (70 men and 50 women). More comprehensive investigations were made by Lysholm et al. (1934), Liljestrand et al. (1939), and Biorck (1944), all using the same method of biplane teleoroentgenography. Later on,

Person	Measures in picture scale						V. cc in picture scale			V. cc in real scale		
	d_1	d_2	d_3	h	A_f	A	1	2	3	1	2	3
A S	17	14	12.5	12.3	172.3	126.0	1435	1555	1500	1150	1240	1210
M L	14	12	9.5	13.7	135.5	102.8	858	835	864	690	670	690
O P												
before treatment	17.5	15	15.5	13.5	187.5	160.3	1940	2140	1890	1560	1720	1520
after "	16	13	12.5	13.0	159.2	130.2	1330	1360	1355	1070	1090	1090

1. $V = \frac{2}{3} A_f \, d_3$ (Kahlstorf's primary ellipsoid formula)

2. $V = \frac{\pi}{6} d_1 \, d_2 \, d_3$ (Jonsell's formula)

3. $V = \frac{8}{3\pi} \frac{A_f \, A}{h}$ (B. Andersson's formula based on planimetrically determined frontal and sagittal surface when the heart is approximated to an ellipsoid)

Fig. 4-189. Heart volume determinations calculated by using the three formulas

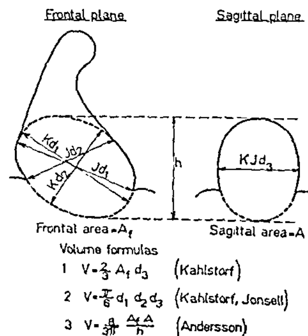


Fig. 4-188. Heart volume determination by biplane roentgenography.

termining the volume of the heart by using two orthogonal projections. one frontal, the other sagittal and parallel to the spinal column (Fig. 4-188)

If the heart is an ellipsoid with two *symmetrical* planes parallel to those of the projections, the following formulas can be used for determination of its volume.

$$V = \tfrac{2}{3}A_f d_3 \qquad (1)$$

$$V = \pi/6 d_1 d_2 d_3 \qquad (2)$$

where A_f = the frontal area of the heart
d_1, d_2 = length of the principal axes of A_f
d_3 = depth of the heart orthogonal (sagittal) to the frontal plane

Even if one uses these formulas when the projection planes are not symmetrical planes of the ellipsoid, one still obtains an approximate volume $V' > V$, as proved by Andersson *In actual patients,* the difference between V' and V is at most 2 to 3 per cent of the volume of V. Rohrer and Kahlstorf suggested that the factor 2/3 in formula (1) be replaced by 0 63. Benedetti and Bollini, and later on Poppi, Lysholm, and Nylin and coworkers, suggested different formulas for the measurement of heart *volume.* That suggested *by the author is* derived from studies of Kahlstorf (1932).

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surface in men and 450 cm³ in women, generally excludes congestive phenomena. There are a few exceptions, for example chronic pericarditis, especially with calcification.

A normal heart volume usually indicates that *the cardiac reserve is not decreased*, except in acute coronary artery disease and in *some cases of cor pulmonale* Although in most cases of acute coronary thrombosis the heart is of normal size, in the long run it often dilates and a greater heart volume obtains.

In the early stages of many cardiovascular diseases, such as coronary sclerosis, hypertension, acquired valvular disease, and congenital heart disease, and in cases of different cardiovascular *syndromes due to myxedema*, thyrotoxicosis, anemia, and beriberi, the heart dilates and the heart volume increases. Besides the cardiac dilatation observed in the above conditions, there also is *hypertrophy of the heart muscle*, however, muscular hypertrophy in general plays a minor role in the enlargement P D. White reported a patient whose heart muscle weighed 1,000 Gm, but this is very unusual

The increased volume of the heart in cardiovascular *disease is evidence of the increased* burden upon the heart and, the more the heart volume increases, the more the cardiac reserve *is reduced. It is, of course, convenient to have* a figure which tells whether the heart is enlarged or not, and the degree of cardiac enlargement. The author's method for determining heart volume *is of great importance in* the handling of patients. Furthermore, repeated heart volume determinations are useful in order to follow the effects of therapy (digitalis, mercurials, etc.).

It is not unusual to observe pronounced changes *in heart volume after treatment, even in ambulatory* patients. A 46-year-old man complained of shortness of breath His body weight was 96 kg and he was *advised to decrease his body weight to* 82 kg, but this did not help. When examined, he showed all signs of heart failure, with edema of the legs, *elevated* venous pressure (22 cm water), and pulmonary congestion. He also had pronounced hypertension with a blood pressure of 260/150 His heart volume was considerably increased The total volume amounted to 1,710 cm³ or 1,040 cm³/m² of body surface Medical treatment was started with Serpasil, Cedilanid, and a weekly injection of a mercurial diuretic There was gradual improvement, and after 5 months of treatment without bed rest the heart volume was reduced to

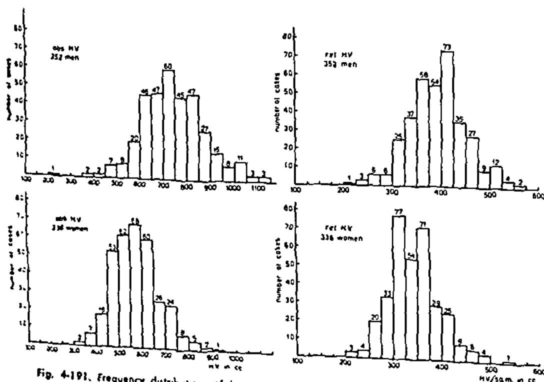


Fig. 4-191. Frequency distributions of heart volumes in healthy adults (absolute *heart volume* and heart volume per square meter body surface).

Grewin (1949) published a comprehensive series using the orthodiagraphic method. Kjellberg et al. also published the data of a smaller group (64 men and 55 women) obtained by using a special technique.

Maurea, Nylin, and Sollberger collected a carefully selected series of over 700 normal individuals observed from 1943 to 1954. All cases were submitted to repeated observations in the cardiac clinic and were found to be free from any evidence of heart or lung disease. Half were men and the other half women; all were adults with normal body weights. The distribution of the normal values is presented in Fig 4-191

Based on this large normal series, a more thorough statistical analysis has been made and correlations between heart volume and age, weight, body surface, oxygen consumption at rest (basal metabolism), and after Nylin's heart function test have been worked out.

The correlation between heart volume and *age* is very low. There is a definite positive correlation between heart volume and *body weight*, body surface, and basal metabolism, and all of them with about the same magnitude of the correlation coefficients Without going into details, the statistical analysis has shown that the "tendential" error of heart volume calculated per square meter of body surface is much less than that of heart volume per kilogram of body weight. The author therefore is of the opinion that it is sound to relate heart volume to body surface.

Lind et al. (1950) made a comprehensive study of heart volume in *children*, covering 202 cases of different ages from birth to one year of age. He, too, found a close correlation between heart volume and body surface with a very high correlation coefficient.

CHANGES IN HEART VOLUME IN PATHOLOGICAL CONDITIONS

It is the author's experience that a normal heart volume, i.e., up to 500 cm³/m² of body

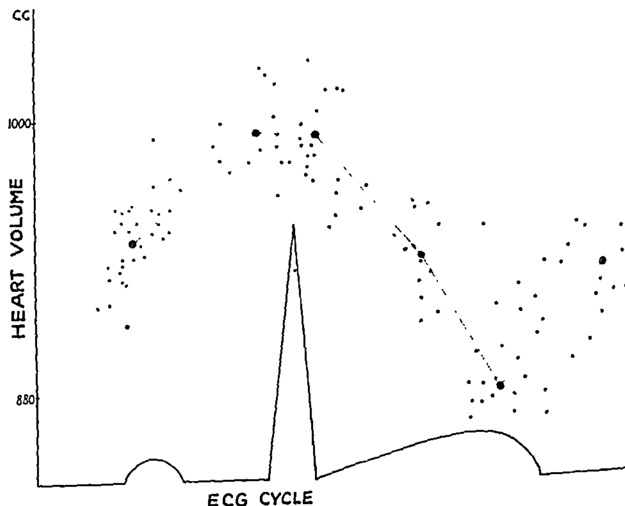


Fig. 4-190. Variations in heart volume during the different phases of the heart cycle (7 cases).

surface in men and 450 cm³ in women, generally excludes congestive phenomena. There are a few exceptions, for example chronic pericarditis, especially with calcification

A normal heart volume usually indicates that *the cardiac reserve is not decreased*, except in acute coronary artery disease and in some cases of cor pulmonale. Although *in most cases of acute coronary thrombosis the heart is* of normal size, in the long run it often dilates and a greater heart volume obtains.

In the early stages of many cardiovascular diseases, such as coronary sclerosis, hypertension, acquired valvular disease, and congenital heart disease, and in cases of different cardiovascular syndromes *due to myxedema*, thyrotoxicosis, anemia, and beriberi, the heart dilates and the heart volume increases. Besides the cardiac dilatation observed in the above conditions, there also is *hypertrophy of the heart muscle*, however, muscular hypertrophy in general plays a minor role in the enlargement. P. D. White reported a patient whose heart muscle weighed 1,000 Gm, but this is very unusual

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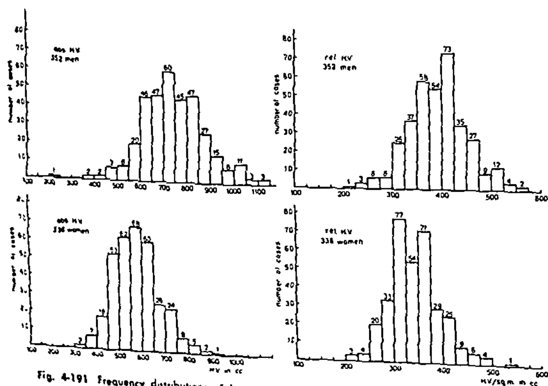


Fig. 4-191 Frequency distributions of heart volumes in healthy adults (absolute heart volume and heart volume per square meter body surface).

1,040 cm^3 or 580 cm^3/m^2 of body surface. His residual blood volume must have been reduced by more than half a liter (Fig. 4-192).

There are other rare cases of increased heart volume. Among them, one should mention *von Gierke's disease* of young children; an unusual disease, chiefly described by R. Levy (cardiac hypertrophy of unknown etiology in young adults), and the pronounced increase of cardiac size in *toxoplasmosis* described by Paully, Jones, Green, and Kane. It is probable that in some tropical diseases, like *Chagas' disease*, a pronounced increase in heart volume will be found.

The author has started to make a statistical study of the heart volume in different cardiovascular diseases. The first group included 200 cases of mitral stenosis, over half of which were compensated, while the other half was decompensated Among the compensated cases of mitral stenosis, there are many within normal limits of heart volume but about one-half of the cases have volumes which are distributed much above the normal variations.

The author has also plotted both compensated and decompensated cases in hypertension and observed enormous variations in the heart volume. The material consisted of 275 men and 309 women. Of the decompensated patients, only four men and three women had normal heart volumes.

HEART VOLUME AND RESIDUAL BLOOD VOLUME OF THE HEART

The volume of blood left in the heart cavities at the end of systolic contraction in normal subjects is not known. It is highly probable that the right ventricle, and perhaps the left, do not empty completely during systole. Wegelius found with his technique (kineroentgenography) that even healthy children do not empty their heart cavities completely. It

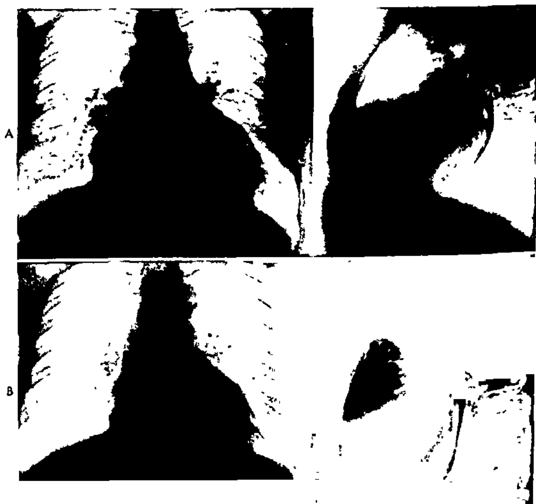


Fig. 4-192. Hypertension (260/150) and heart failure. changes in heart volume after 5 months of treatment, from 1,710 cm^3 (A) to 1,090 cm^3 (B).

is known that the heart volume at autopsy is about 300 cm³ while the heart volume at x-ray examination is twice as great in normal persons. This speaks in favor of the presumption that the heart contains a certain volume of residual blood in physiological conditions. The acute changes in heart volume during certain physiological activities are sometimes pronounced, for example this is true for the maneuvers of Valsalva and Muller, for the difference between recumbency and the erect position. Certain findings indicate that there must be pronounced changes in the volume of residual blood in the heart. A study of the residual blood in the heart in the standing and recumbent positions was made by Malmstrom and the author (1942). They found that circulation time is more rapid in the standing than in the recumbent position, owing to the mixing with different amounts of residual blood; circulation times in pathological cases were found to be quite prolonged in subjects with a dilated heart. They came to the conclusion that *the slow circulation was actually due to the increased amount of residual blood within the cardiac chambers.*

This has been confirmed by present-day, more objective methods, like intravenous injection of radioactive red cells tagged with P^{32} or Th^{82}, a method the author has used for 15 years. After the injection, blood samples are collected from an artery, radioactivity is measured, and a so-called dilution curve is plotted. From these curves it is possible to calculate, not only cardiac output, but also, *the thoracic pool, i.e., the volume of blood* contained in both the heart and the lungs (Nylin and Celander, 1950). In the case of Figs. 4-193 and 194, the thoracic pool amounted to 1.2 liters. The heart volume was 629 cm³ (normal) and the heart probably contained at least 200 ml of residual blood; thus, the blood content of the lungs would be about 1,000 ml.

When the heart dilates, the volume of residual blood in the heart increases. An example of enlarged heart is shown in a case of mitral stenosis plus tricuspid insufficiency (*Fig. 4-195*) where the configuration of the heart resembled that of an ellipsoid. The heart volume was 4,160 cm³. The thoracic pool volume was found to be 4,040 ml while that of the heart muscle was 630 cm³. If one subtracts the volume of the heart muscle and that of a hydropericardium from the heart volume determined during life, one obtains a value of *3,430 ml for the residual blood volume of the heart.* It is probable that the blood content of the lungs in this case was below the normal value of 1,000 ml. Therefore, it is probable that the value of 4,040 ml for the thoracic pool was an accurate finding.



Fig. 4-193. Normal heart

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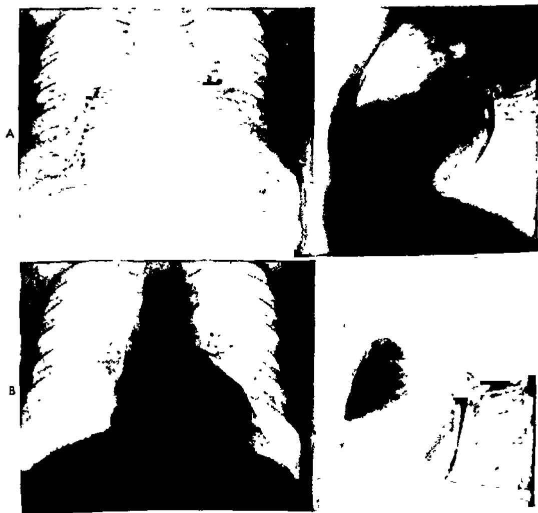


Fig. 4-192. Hypertension (260/150) and heart failure changes in heart volume after 5 months of treatment, from 1,710 cm^3 (A) to 1,090 cm^3 (B).

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Fig. 4-193. Normal heart.

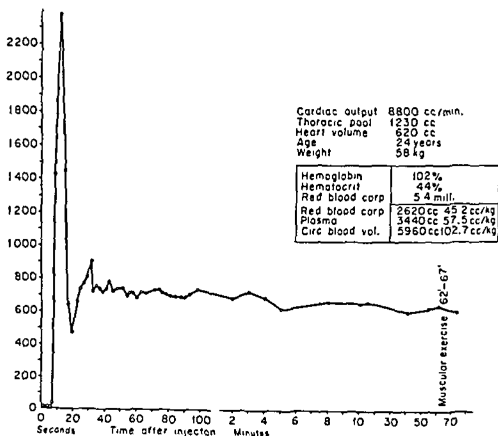


Fig. 4-194. Dilution curve of arterial blood after intravenous injection of labeled blood, normal subject



Fig. 4-195. Enlarged heart, with a volume of 4,040 cm³, from a patient with mitral stenosis and tricuspid insufficiency.

In heart failure with dilatation of the heart, one finds a pronounced increase in both the circulating blood volume and the *circulation* time, determined by the radioactive-cell method One would expect a close correlation between total blood volume and heart volume, and this was found in normal cases by Sjostrand, Kjellberg, and Rudhe. In the author's hands, a correlation was found both in normal and in dilated hearts, but not a close one. On the other hand, the author found a strikingly high correlation between the heart volume and the thoracic pool volume In pathological cases, the thoracic pool volume is *the expression of the increased volume of* residual blood in the dilated heart.

Even if the hearts of different individuals, healthy or diseased, differ in shape so that no formulas fulfill the demands of exactness, it has been proved that the method of Kahlstorf, Liljestrand, Lysholm, Nylin, and Jonsell gives better information about cardiac size than any other method. Hallert's photogrammetric method might be more exact but is impractical in clinical practice.

CONCLUSIONS

1. A correct evaluation of the heart size cannot be made from the frontal surface by orthodiagraphy or teleoroentgenography, but it can be made with biplane teleoroentgenography.

2. *Total heart volume should* be correlated to body surface. The upper limit for the normal heart volume is 500 cm^3/m^2 in men and 450 cm^3/m^2 in women.

3. Treatment of cardiac cases is often followed by reduction in heart volume. Therefore, repeated measurements of the heart volume give the cardiologist important information

4. The physiological and clinical changes in heart volume largely depend on changes in the volume of residual blood in the heart. It *is probable that one of the first signs of de*creased cardiac efficiency is an increase in residual blood and heart volume.

5. Intravenous injection of radioactive red cells followed by sampling from an artery, gives objective information about circulation time and mixing with the residual blood Calculation of the dilution curve makes it possible to estimate the blood content of the heart and lungs—"the thoracic pool"—which is rather constant in normal hearts.

6. In conditions accompanied by cardiac dilatation, a close correlation between the thoracic pool volume and the heart volume can be found

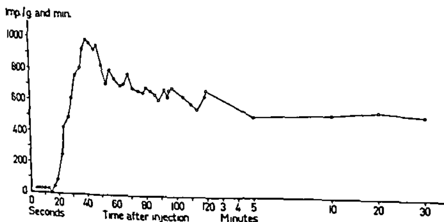


Fig. 4-196. Dilution curve of arterial blood after injection of Th^{B2}-labeled blood in a patient with mitral stenosis and mitral-aortic-tricuspid insufficiency.

14

Studies of cardiac dynamics

KJ. BLUMBERGER AND SIGISBERT MEINERS

Cardiac dynamics is understood to be the work of the heart, in terms of pressure and volume, performed during a definite time. Owing to the ability of the heart to adapt itself to changing conditions, and particularly to modifications of peripheral demands, the three important parameters of cardiac dynamics, viz., pressure, volume, and time, are subject to such great changes that their clinical diagnostic application seems at first highly problematic. However, the contraction times of the healthy heart, apart from short initial reactions, vary much less than pressure and volume. In fact, they show such a stability that their measurement may supply valuable diagnostic information. This fact induced Edens to suggest the determination of the most important phases of cardiac contraction (periods of tension and ejection) by means of simultaneous registration of several phenomena.

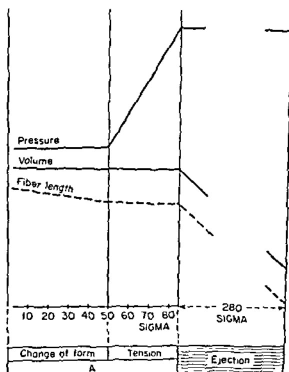


Fig. 4-197. Schematic representation of time changes in fiber length and ventricular volume and pressure during systole. (Sigma = 0.001 sec.)

Figure 4-197 represents schematically the changes of pressure in the left ventricle during the course of one cardiac systole and gives a picture of the different phases of cardiac contraction. The whole of systole is divided into several phases, the first is essentially isometric and called the *period of tension,* during this period, the length of the muscle fibers remains practically unchanged, as confirmed by a tracing of ventricular volume, and the tension around the cardiac contents increases. The period of tension actually consists of two parts: during the first part, the ventricle changes from an ellipsoid to a more spheroid form while the pressure remains constant and the muscle fibers are shortened but slightly, this is called the *transformation period* During the second part, the pressure rises within the ventricle while the volume remains constant, this is called the period of rising pressure or *isometric contraction* When the pressure of the ventricular chamber has reached the level of the aortic diastolic pressure, another important phase of systole begins, the phase of ejection. During this phase, the ventricle ejects its contents by a shortening of its muscle fibers without a change in its pressure, this *isotonic phase* of cardiac contraction is, therefore, called *ejection period.*

Several methods have been developed for the determination of these phases of contraction. After taking electrocardiograms and phonocardiograms, von Dungern measured the tension period from the beginning of the Q wave to the beginning of the ejection sound (a vibration of the 1st heart sound); and the ejection period from the beginning of the ejection sound to the beginning of the 2d heart sound In spite of its good theoretical basis, practical application of this method is often rendered difficult by the frequently uncertain limits of the ejection sound.

Reindell and Klepzig based their method on tracings of apex beat, and of carotid and femoral pulses, and measured the tension period from the Q wave of the ECG to the foot of the carotid pulse wave, minus the delay of this wave This delay is calculated by measuring pulse velocity and applying this velocity to the distance from the aortic valve to the point where the carotid pulse is recorded. This method, like the one previously cited, is based on sound principles but is of difficult application since there are sources of error in the measurement of velocity, as well as involved technical and mathematical calculations.

When only two phenomena can be recorded simultaneously with the same apparatus, Maas has recommended the following procedure.

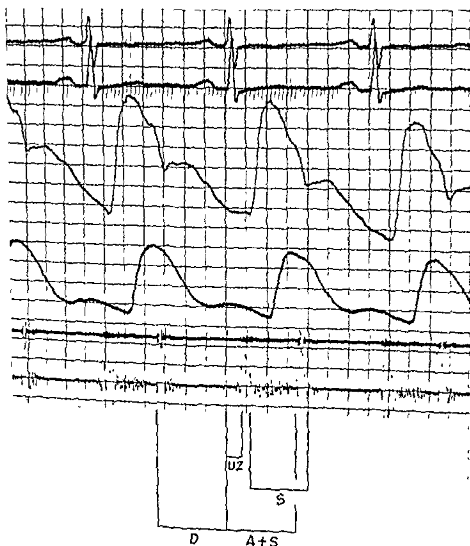


Fig 4-198 Determination of diastole, D, systole, A + S, ejection time, S, and transformation time, UZ, from the electrocardiogram, carotid pulse tracing, and phonocardiogram

The carotid tracing is recorded first with a phonocardiogram, then with the ECG. The time delay is reckoned by measuring the distance between the beginning of the 2d heart sound and the incisura of the carotid pulse, and this value is deducted from the total systolic period, which is measured from the beginning of the Q wave to the incisura of the carotid pulse. The ejection time is determined through the carotid tracing, and the tension time is represented by the difference between the total systolic period and the ejection period.

Below is a detailed description of the method of Blumberger and Schultz, which has found wide applications owing to its accuracy and its comparatively modest requirements in regard to both apparatus and time needed for calculations. In this method, the phases of cardiac contraction are determined from three tracings simultaneously recorded. an electrocardiogram, a tracing of central pulse, and a phonocardiogram. The principle of the method may be described schematically as follows (*Fig.* 4-198)

1. Determination of *total systole* by means of the ECG and phonocardiogram:

Total systole = distance from beginning of Q wave to beginning of the following 2d sound (1)

2. Determination of *ejection time* by means of either the carotid or subclavian pulse tracing:

Ejection time = distance from foot to incisura (of the pulse used) (2)

3. Calculation of tension period, Eq. (1) minus Eq (2):

Tension period = total systole minus ejection time (3)

4. Calculation of hemodynamic ratio:

Hemodynamic ratio = ejection time divided by tension period (4)

This is always done because the durations of these periods vary and are influenced by different factors, some of which act in a concordant and some in a discordant way on the two phases of systole.[1] The ratio is generally between 2.5 and 4.0; i.e., the ejection period is from 2.5 to 4 0 times longer than the tension period.

5. Measurement of *duration of diastole* from the ECG and phonocardiogram:

Diastole = distance from beginning of preceding 2d sound to beginning of following Q wave (5)

If one studies one particular cardiac cycle, the diastole *preceding* the systole is measured, since only this has influence on the tension and ejection periods of the subsequent cycle because of different ventricular filling and of metabolic changes occurring in the myocardium during this period.

6. Calculation of the pulse period:

Pulse period = total systole + diastole (6)

If the various sections or parts of the 1st sound can be measured, the preceding method can be supplemented by Holldack's calculation of the two components of the tension period, viz., the transformation and the rising pressure periods, as follows:

7. Determination of transformation time:

Transformation time = distance from the beginning of the Q wave to beginning of the main portion of the 1st sound (7)

8 Calculation of rising pressure time:

Rising pressure time = tension time minus transformation time (8)

Since all these values fluctuate from beat to beat, they are determined as the arithmetic mean from 10 beats if the subject has regular rhythm, and from at least 20 beats in cases of arrhythmia. In case of extrasystoles, the mean values are calculated separately for the normal, the extrasystolic, and the postextrasystolic beats.

[1] The ejection period becomes longer, the tension period shorter, and the ratio larger under stroke simultaneously with a determination of cardiac dynamics

In order to keep the necessary calculations within reasonable limits, the following detailed procedure is recommended. The part of the graph to be measured is numbered, starting from an arbitrary point, so as to make it possible to fix the points to be determined by a definite numerical value. First the numerical values for the beginning of the 1st and 2d heart sounds are determined for 10 or 20 heartbeats respectively, as well as the beginning of the Q wave in the ECG, the duration of the ejection period is then deduced as the time value of a central pulse tracing. Second the tension and ejection times are calculated from these numerical time values, then the hemodynamic ratio, the duration of diastole and that of total systole, as well as the transformation and rising pressure times, according to the following scheme.

1st row: Numerical value of the main segment of sound I from tracing	
2d row: Numerical value of sound II from tracing	
3rd row. Numerical value of Q wave from tracing	
4th row. Numerical value of preceding sound II from row (1)	
5th row Duration of diastole [a]	row (3) minus row (4)
6th row: Duration of total systole [a]	row (2) minus row (3)
7th row. Ejection period [a]	from graph
8th row Tension period [a]	row (6) minus row (7)
9th row: Hemodynamic ratio (ejection period/tension period)	row (7) divided by row (8)
10th row: Duration of pulse [a]	row (5) plus row (6)
11th row Transformation period [a]	row (1) minus row (3)
12th row Rising pressure period [a]	row (8) minus row (11)

The arithmetic mean from 10 or 20 single values, respectively, of rows (5) to (12) represents the final result

In order to interpret in a clinical diagnostic manner the values for tension and ejection periods, calculated by the above method, a knowledge of the normal values and their physiological fluctuations is necessary. It is particularly important to know the factors influencing the various time phases of heart contraction. Normal values and physiological fluctuations are given in Table 4-43

Tension time (duration of the tension period) does not depend unequivocally on frequency. Trained athletes and subjects with high vagal tonus have an upper limit of 120 μsec In patients, such high values can be regarded as normal only if they are not shortened by an injection of 0 25 mg of strophanthin. (Digitalis-like drugs abbreviate the prolonged tension period of heart failure) Tension time depends on the extent of the initial tension and contractility of the cardiac fibers, on the presystolic pressure-difference between ventricular and aortic pressures, and on the action of the cardiac nerves (Figs 4-199 and 200) Tension time is abbreviated by increases in initial tension, contractile force, and sympathetic nerve impulses, it is prolonged by increases in vagal impulses and presystolic pressure-difference

[a] All numerical values, i e, rows 5 to 8 and 10 to 12, are given for reasons of clarity in μsec, or thousandths of a second.

TABLE 4-43. DYNAMICS OF THE LEFT HEART

Pulse phase	*Normal duration, μsec*
Tension period	50–105 (most frequently 70–100)
Ejection period	200–310 (exceptionally up to 320)
Transformation time	40–70 *
Rising pressure time	15–45 *
Hemodynamic ratio	2 5–5 0 (exceptionally, at rest, up to 5 0)

* According to Holldack.

Ejection time (duration of the ejection period) depends upon the frequency according to the equation

$$S = 6\,2 \times 2\,9\sqrt{T}$$

where S = ejection time in sec
T = R-R interval in sec

Ejection time depends also upon the contractile force and the rate and velocity of ejection, an increase in any of these causes an abbreviation. It further depends upon diastolic filling, stroke volume, and peripheral resistance, an increase in any of these causes a prolongation.

Theoretically, the same conditions hold true

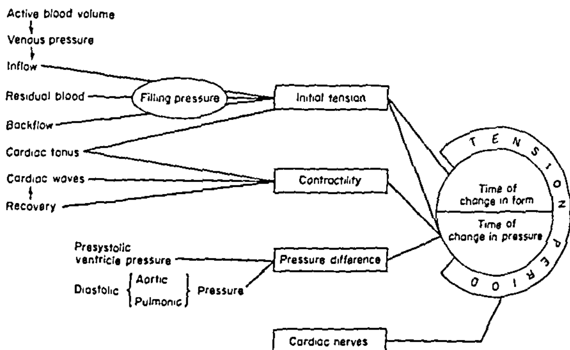


Fig. 4-199. Tension time (transformation time plus rising pressure time) as a function of different cardiac and circulatory factors. *(From Blumberger, 1957.)*

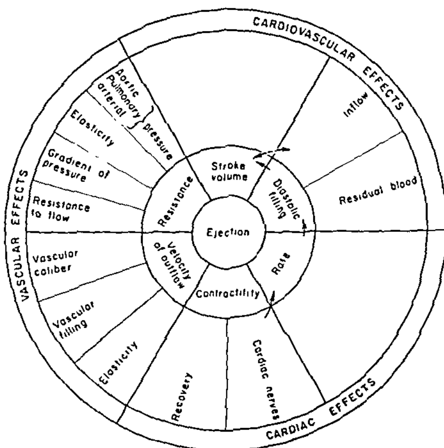


Fig. 4-200. Ejection time as function of cardiac, vascular, and circulatory factors. *(From Blumberger, 1957.)*

for the right ventricle as for the left (H Straub). However, few experiments have been made on the measurement of systolic phases from cardiac catheterization tracings. Therefore, exact normal values for tension and ejection times of the right ventricle are not completely known

Since the right ventricle is normally weaker than the left, it is forced to adjust its activity to the pace of the left ventricle and is not completely independent in its movements. The rise of pressure in the right ventricle is slightly delayed and slower than that in the left because of its particular shape (the right ventricle is wrapped around the left) and its *smaller muscular mass. Tension time is longer.* Since the pressure difference between right ventricle and pulmonary artery are also smaller than between the left ventricle and aorta, right ventricular ejection time is shorter. Consequently the systole of both ventricles is approximately (not exactly) the same length. It can happen that the left ventricle must adjust its contraction to that of the right, if the left ventricle is weak and the right has undergone hypertrophy (Blumberger).

With the help of simultaneously recorded graphs for ECG, apex beat, and jugular tracing (electrokymograms are not equally accurate), it is possible to determine the relaxation period and the duration of both rapid and slow filling times. The results of these calculations are at present too few to be used for research in cardiac dynamics.

15

Endocardial and epicardial electrocardiograms

DEMETRIO SODI PALLARES
AND MARIO R. TESTELLI

Endocardial electrocardiograms are obtained during right and left heart catheterization by means of endocardial catheter electrodes or through a column of saline solution (or blood) in the catheter acting as a linear conductor. The proximal end of the catheter is coupled to a "central terminal" of Wilson, and the recording is made together with a simultaneous peripheral lead for reference. The amplification of the recording apparatus is properly adjusted, lesser amplification is needed for the potentials derived from the ventricles.

Epicardial electrocardiograms are obtained by "direct leads" in the course of thoracic surgery. "Semidirect leads," such as the esophageal, bronchial, and those recorded during catheterization of the coronary sinus or the thoracic aorta, are usually analyzed as leads somewhat similar to the epicardial leads.

The following will facilitate the interpretation of records obtained with endocardial leads.

The unipolar intraventricular leads may be considered as *direct leads* when the exploring electrode is in contact with the endocardial surface, and as *semidirect leads* when the electrode is removed from the endocardium. In the first instance, the potential recorded by these leads is defined as the voltage measured between the exploring electrode and a second electrode placed at an "infinite" distance. At points more or less remote from the endocardium this potential is proportional to the component of the dipole moment in the direction of that point where the exploring electrode is located in the cardiac chamber. The reason for this (McFee and Johnston) is that the field of the lead formed by the exploring electrode and the electrode at "infinity" is then no longer uniform. At the exploring electrode, the flow lines of current are crowding together, i.e., the lead-field current is more intense there, this, in turn, means that the voltage in the lead is more sensitive to electromotive forces located there than to distant ones.

It is obvious that in a direct endocardial lead with the exploring electrode in contact with the surface, the dipole theory is not valid.

Using the concept of the lead field, it is possible to derive the following formula for the relation between the potential and the above-mentioned electromotive forces.

$$v = \vec{J}\,\vec{e} = \left(\frac{\vec{1r}}{4\pi r^2}\right)\vec{e}$$

where $\vec{J}$ = the magnitude and direction of the flow of current ("vector field") at any given point

$\vec{e}$ = the electromotive forces

$\vec{1r}$ = a unit vector directed along the line going from the electromotive force to the exploring electrode

This formula states that the current density of the current flowing into the exploring electrode decreases inversely with the square of the distance from it, and it is directed toward it. The factor 4π is necessary because the area of a sphere of radius 1 about the electrode is 4π.

An indifferent electrode is a reference electrode giving the same relative potential to the exploring electrode that it would have relative to infinity if it and the electromotive forces of the heart were part of an infinite homogeneous conductor. Since the voltage will be the same only if the lead field is the same, it follows that "an indifferent electrode is one which, together with the exploring electrode, produces a field within the heart which appears to radiate out from the exploring electrode in straight lines, and whose intensity there varies inversely with 4π times the square of the distance to the exploring electrode" (McFee and Johnston).

When the endocardial exploring electrode is located at atrial levels, the lead can be considered as a direct unipolar lead only for the electrical forces originated from the atrial musculature and only if the electrode is in contact with the endocardium. Even in this case, such a lead must be analyzed as a semidirect lead, or even as a distant unipolar lead for the ventricular potentials It is apparent that the use of the central terminal or any other device that reduces the density of the current in the distant electrode in comparison with that at the exploring electrode would be extremely convenient. In these cases, the dipole concept may or may not apply, depending upon the distance between the electrode at different atrial levels and the ventricular potentials

When the exploring electrode is near the ventricular forces (lower atrial levels), the tracing shows important local effects, again suggesting that the dipole concept does not hold It should, then, be admitted that in the Stratton formula, the effect of the quadrupoles and octupoles is probably significant, and that this explains the above-mentioned local effects In such instances, the lead could be better analyzed by the Poisson integral, considering that all the charges produced at any moment of ventricular activation are included within a sphere of the smallest adequate radius The unipolar pattern obtained by such an electrode will be similar to that obtained at the surface of that imaginary sphere close to the exploring electrode

An example will illustrate this discussion In case of right bundle branch block, according to the dipole theory, the right septal mass and the right ventricle are positive during most of the time of ventricular activation, while the left septal mass and the left ventricle are mainly negative In fact, unipolar leads within the right ventricle record mainly positive deflections, and within the left ventricle mainly negative deflections. Nevertheless, when the exploring electrode is below the tricuspid valve within the right ventricle, negative deflections can often be recorded, even if the electrode is in the positive side of the field. It follows, then, that the dipole concept does not hold true, probably because of the proximity of the exploring electrode to the sites of origin of local forces (local effects). Consequently, according to the Poisson integral, one has to look for some similar negativity at some other place on the endocardial surface. In fact, similar patterns are obtained at the superior and posterior region of the right septal surface, which is known to be formed by the left septal mass Undoubtedly, therefore, in order to obtain a good electrocardiographic interpretation, one needs to know where to use the Stratton formula, the Poisson integral, or both at the same time

NORMAL ATRIAL POTENTIALS

The normal wave of activation, after originating from the SA node, spreads in a radial way to the atrial musculature at an average speed of 1,000 mm/sec. The first regions to be activated are in the right atrium near the SA node. Activation of the left atrium starts in man about 0.035 sec later (Groedel and Borchard, Reynolds), and in the dog, 0.015 sec later. The last regions to undergo activation are in the posterior and inferior aspect of the left atrium. The total activation time for both atria averages 0.050 sec in the dog, and 0.085 sec in man It should be noted that in the sequence of their activations, the two atria present a certain degree of asynchronism, even though their phases are largely superimposed. The significance of this time relationship will be seen when atrial enlargement is described.

Epicardial and intracavitary leads record similar potentials at corresponding atrial levels because the thin atrial wall acts as a simple electrical surface. The terminology, which is generally accepted, is that proposed by Hecht A better understanding of the various unipolar waves can be obtained by a vectorial representation of the resultant electrical forces (Fig. 4-201).

The vector of right atrial activation (SAPr), which corresponds to the first half of the P loop, is directed downward and slightly anteriorly. Near the SA node, the atrial complex is characterized by a negative P wave with a rapid intrinsic deflection and a voltage greater than that of the ventricular complex At higher atrial levels, in the superior vena cava, and in the pulmonary artery, the P wave is negative and smaller At middle atrial levels, a *positive, preintrinsic deflection* appears, which increases in voltage as the electrode moves away from the SA node In the lower right atrium, in the

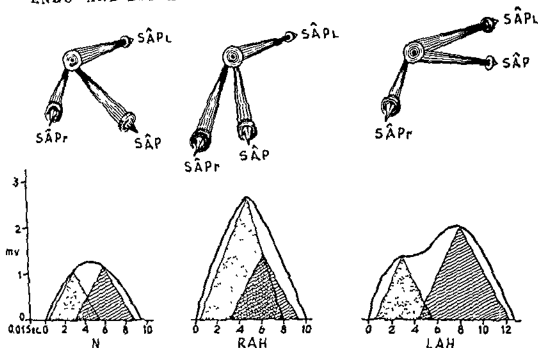


Fig 4-201. Schematic representation of the main vectors of atrial activation. Vector of right atrial activation (SÂPr); vector of left atrial activation (SÂPl), vector of mean atrial activation (SÂP) N, normal condition, RAH, right atrial hypertrophy, LAH, left atrial hypertrophy

P-Ta↑

Fig. 4-202. Intermittent second-degree AV block Tracing obtained at mid-right atrium. Note the negative Ta wave when the AV conduction fails Duration of atrial systole (P-Ta) is 0.40 sec.

inferior vena cava, and in the right ventricle, the P wave is positive and similar to a peripheral P wave

The vector of *left atrial* activation (SÂPL), which corresponds to the second half of the P loop, is a right-to-left vector directed toward the back and slightly *upwards* The typical atrial pattern at the midleft atrium is a diphasic P wave, and a positive P wave in the posterolateral regions. Quite often, *there is* a small positive deflection or a small notch preceding the atrial complex, which is due to the activation of the *right atrium* Near the mitral valve and in the left ventricle, the *P becomes positive* and it assumes the characteristics of a peripheral P wave

The *atrial recovery wave* (Ta) is seen as a slow, *negative* deflection only in cases of AV block (Fig 4-202), *when the* wave of atrial recovery is separated from the QRS of ven-

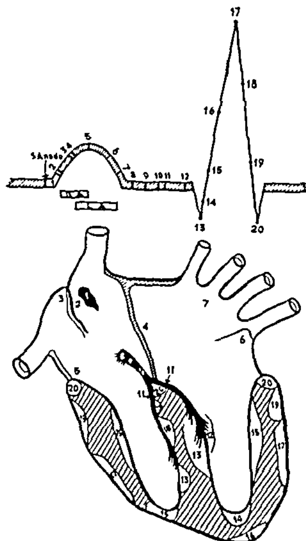


Fig. 4-203. Scheme of the sequence of atrial and ventricular activation correlated with lead 2. The arrow indicates the beginning of the activation of the SA node (point 1). *RA*, total duration of activation of the right atrium, *LA*, the same for the left atrium. The main points in the sequence of atrial activation (points 2 to 7) are referred to the peripheral P wave. The sequence of activation of the specific conducting tissue (points 8 to 12) is correlated with the P-R interval as follows: 8, head of the AV node, 9, tail of the AV node, 10, bundle of His; 11, left and right bundle branches, 12, first ramifications of the left bundle branch. The main points in the sequence of ventricular activation (points 13 to 20) are referred to the peripheral QRS. The first portions of ventricular musculature to be activated are in the middle third of the left septal mass (point 13, peak of the peripheral Q wave); the latest portions are at the base of both free ventricular walls and both septal masses (point 20, peak of the peripheral S wave). The peak of the R wave corresponds mainly to the activation of the subepicardial portions of the free left ventricular wall (point 17).

tricular activation. Atrial systole (P-Ta) lasts 0.40 to 0.60 sec, i.e., is much longer than ventricular systole (Q-T).

NORMAL VENTRICULAR POTENTIALS

The *activation wave travels down* from the AV node along the bundle of His and the two branches (Fig. 4-203). The earliest evidence of activity of the ventricular musculature is recorded in the middle third of the left septal surface, at the level of the first ramifications of the left bundle branch (Sodi-Pallares et al., 1951). The sequence of normal ventricular activation can be represented in three main vectors, referred to a heart with an intermediate position and without abnormal rotation along its anatomic axis (Fig 4-204). The same reference will be adhered to in subsequent descriptions of abnormal vectors.

The electrical forces from the anatomically more important left septum overbalance those from the right septum, which is activated 0 010 to 0 015 sec later at its surface. The resultant *electrical manifestation of this early ventricular activation is a first septal vector* (I) (Fig. 4-204), which is directed anteriorly and to the right toward the base of the anterior right papillary muscle and the trabecular zone, and pointing upward or downward in relation to the anatomic position of the heart.

In the right ventricle, the first septal vector (I) is represented by an r wave, which is greater near the apex and is small or even absent at other levels of this cavity. At the same time, a small degree of negativity is recorded in both atria and in the left ventricle. However, *an initial positivity in the left ventricle can be normally registered in dogs when the exploring electrode is in contact with higher and lower regions of the left septal surface* (Medrano et al.). These experimental findings can explain the small initial r recorded in the left ventricular cavity of man, in the absence of incomplete left bundle branch block (Testelli, Hellerstein).

After traversing the two bundles and their ramifications, the activation process reaches the subendocardium of both ventricles. Because of the relative thinness of the free *right* ventricular wall, the latter is rapidly activated from the endocardium to the epicardium. On the other hand, the activation vector of the free *left* ventricular wall is mainly due to the depolarization of the subepicardial layers (Kennamer

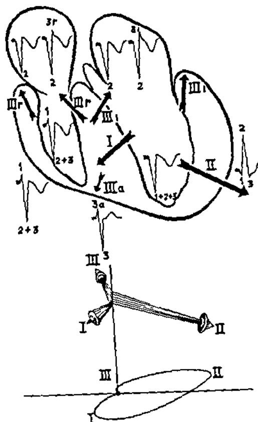


Fig 4-204. Schematic representation of the most common unipolar endocardial and epicardial patterns referred to the main vectors of ventricular activation with normal conduction The QRS deflections are marked with arabic numerals, and the corresponding vectors with roman numbers Spatial projection of the vectors and the vectorcardiographic curve in the horizontal plane are represented in the middle and lower parts of the figure. A similar schematic representation will be used in subsequent figures

Vector I, activation of the middle third of the left septal mass, vector II, activation of the free left ventricular wall, vector IIIa, activation of the low right septal mass, vector III, resultant activation vector of basal portions of the left septum and free left ventricular wall (vectors III_l), and of the right septum and free right ventricular wall (vectors IIIr) Note the normal discordance of the left ventricular endocardial and epicardial T waves

et al, Durrer et al, Sodi-Pallares et al, 1955). *The subendocardial portions of the left ventricle do not participate in the formation of these potentials because they present an almost instantaneous and multidirectional activation* The front of the wave of activation forms closed polarized surfaces for which no external electrical field is detectable (Fig 4-205)

The sequence of surface ventricular activation in man has been described by Barbato et al in this order, right paraseptal regions, followed by the apices of both ventricles, then by the intermediate zones, and finally by the basal regions of the anterior and lateral surfaces. The large forces of the free left ventricular wall predominate over those of the right ventricle (10:1 ratio) and give rise to an important vector (II) (Fig 4-204), which is directed posteriorly and to the left, and pointing upward or downward according to the position of the heart (The predominance of the forces due to the left ventricle explains the counterclockwise rotation of the normal vectorcardiogram in the

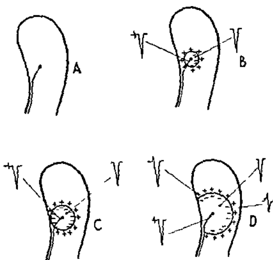


Fig. 4-205. Schematic representation of the activation process of the free left ventricular wall. A Purkinje fiber before being activated B, C, and D. Three stages of activation. B. The front of the activation wave represented to form a closed polarized area, the inside negative to the outside An electrode outside the area records no electrical activity (not depicted in the figure), an electrode inside records only negativity preceded (left of the figure) or not (right of the figure) by the Purkinje potential, depending on the location of the electrode with respect to the same Purkinje fiber C. A further stage of activation The front of the activation wave still forms a closed polarized area D The area opens to the endocardium. Only now an initial positivity is recorded on the positive side of the activation front On the other hand, the negative side of the front may reach some regions of the anatomic epicardium, in which, therefore, entirely negative complexes are recorded

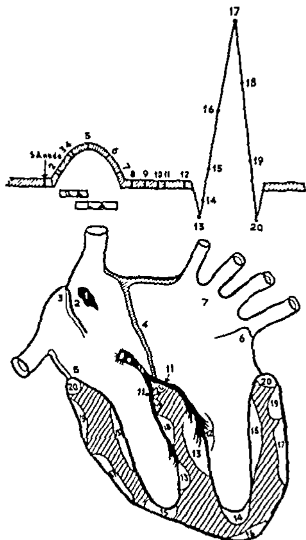


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NORMAL VENTRICULAR POTENTIALS

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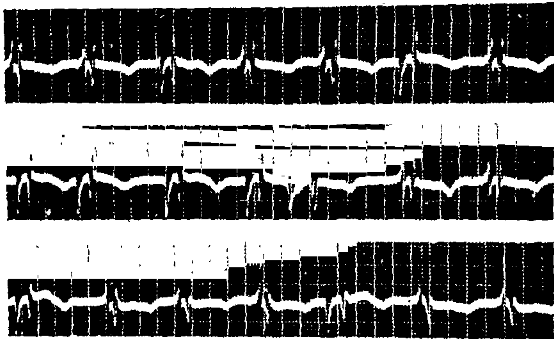


Fig. 4-206. Wandering pacemaker Continuous tracing with the electrode in the high level of the right atrium near the SA node Changing pattern of the P wave with the shifting of the pacemaker: the P wave is negative when the pacemaker is in the SA node, and becomes completely positive when the pacemaker is in the AV node.

sence of any definite pattern (Fig 4-208) Irregular and polymorph "f" waves may be recorded at one atrial level, and *coarse fibrillation* waves at another level or in the opposite *atrium* In such instances, it is hard to define the difference between flutter and fibrillation

ABNORMAL VENTRICULAR POTENTIALS

***Complete Right Bundle Branch Block* (RBBB).** The ventricular activation in complete RBBB may be visualized into four main vectors (Fig 4-209). The activation wave progressing along the left branch reaches the middle portions of the left septal surface and progresses in a normal way through the left septal mass, thus, the *first vector (I)* is similar to the first septal vector of normal ventricular activation. Following this, the right branch being blocked, activation of the free left ventricular wall takes place, *giving rise to a normal vector (II)* This, however, has a lower magnitude because, at the same time, the activation is *crossing* the septum from left to right, a *fact* which partly counterbalances the forces of the free left ventricular wall When the activation wave crosses the septum, it "jumps" the physiologic interseptal "barrier" (Rodríguez and Sodi-Pallares) *to reach and activate* with a slow type of activation the lower parts of the right septal mass in a direction opposite to the normal one This causes an important *vector (III)*, which is directed *anteriorly*, to the right, and slightly upwards The late activation of the middle and upper parts of the right septum, together with high portions of the *free right* ventricular wall, *originates a late vector (IV)*, directed to the right, upwards, and more anteriorly than vector III

The following are the main unipolar characteristics (Fig 4-209) In the left cavities, the complexes are entirely negative because the four vectors are pointing away from the electrode *At the surface* of the free left ventricular wall, the pattern differs from that of the left cavities only for the positivity due to *vector II*. As far as the *right side* is concerned, the normal first septal vector (I) is attended by an initial positivity in both the endocardial and the epicardial leads of the right ventricle. The negativity produced by the normal second vector (II) is counterbalanced by the strong positivity of the left-to-right septal vector (III) A similar positivity is registered at the surface of the

horizontal plane.) At this time, negativity is present in all cardial chambers.

The last regions to be activated are at the base of both ventricular free walls and both septal masses (IIIr and IIIl) (Fig. 4-204), which result in a third important vector (III), directed *posteriorly, to the right, and upwards.* Thus, the inscription of the late R in both atrial cavities is due to electrical forces of the basal septal regions, and is partly contributed also by late activation of basal and posterior regions of the respective ventricle.

With reference to the epicardial and precordial leads, the early septal vector (I) is responsible for the q wave in the left side and for the r wave in the right. The latter is in part due also to the small force of the thin, free right ventricular wall The R wave in the left epicardial leads is due solely to the vector (II) of the free left ventricular wall, while the S wave in the right is partially due to the third vector (III) as well. This last vector (III) is also responsible for the S wave in the left epicardial leads. Vector IIIa represents the electrical forces of the low septal mass, which influence proximity leads (local effects).

The ventricular recovery process is represented by a negative, asymmetric T wave in all cardiac chambers Therefore, normally there is a discordance between endocardial and epicardial, as well as precordial, T waves from the left ventricle

ABNORMAL ATRIAL POTENTIALS

Atrial Enlargements. Hypertrophy of the atria is usually diagnosed when *dilatation* is also present, therefore, the more general term of "enlargement" seems preferable. Atrial enlargements cause an increased voltage and a delayed inscription of the corresponding intrinsicoid deflections and of the respective vectors of activation, resulting in changes of magnitude and orientation of the P loop (Fig 4-201). The recovery process of the atria undergoes secondary alterations, which are reflected on the P-R segment. In diseased states with isolated atrial hypertrophy, abnormalities of a lesser degree are present.

RIGHT ATRIAL ENLARGEMENT The delayed activation of an enlarged right atrium seldom exceeds the activation period of the left atrium. Consequently, the total duration of the P wave is rarely prolonged More important are the changes of the P vector loop, which becomes long and narrow, pointing anteriorly and downwards (Fig. 4-201). Therefore, *tall and peaked P waves* are recorded in the lower right atrium and in the right ventricle, in the right epicardial and precordial leads, and in leads II, III, and aVF. Often, the P waves in V_1 and V_2 *present an evident intrinsicoid deflection; negative P waves* are recorded sometimes in right precordial leads of subjects with vertical hearts.

LEFT ATRIAL ENLARGEMENT. Typically, in the course of mitral stenosis with enlargement of the left atrium, the terminal portion of the P loop becomes enlarged and delayed, pointing to the left and posteriorly, usually upward but sometimes downward (Fig. 4-201). This correlates well with recent investigations of atrial activation in normal and pathologic conditions In the left atrium, the P wave shows an increased voltage and a delayed intrinsicoid deflection. In the right atrium, the delayed activation of the left atrium is shown as a broad, negative postintrinsic deflection of the atrial complex. By direct and endocardial electrocardiography, *the degree of asynchronism between right and left atrial activation in mitral stenosis has been found increased up to three times the normal values.* This is reflected in the characteristic "P mitrale" of the peripheral leads.

Atrial Arrhythmias. NODAL ARRHYTHMIAS. In *nodal rhythm,* as well as in *nodal premature beats,* the endocardial P wave has the opposite direction of the normal P. On account of the ectopic origin of the stimulus, the P wave is negative near the AV node and positive near the SA node. In cases with a *wandering pacemaker,* an electrode in the right atrium registers atrial waves changing with the shifting of the pacemaker (Fig 4-206)

ATRIAL PREMATURE BEATS Atrial premature beats may be produced by the catheter or may originate spontaneously. In the first case, the P wave is *negative* because the activation wave is moving away from the recording electrode, in the second case, the shape of P is related both to the location of the catheter and to the origin of the premature beat

ATRIAL FLUTTER AND FIBRILLATION In *atrial flutter,* prominent "F" waves with rapid intrinsicoid deflections are recorded in both atria (Fig. 4-207) These waves may not be seen in the ventricles because usually lower amplification is used for intraventricular recordings. *Atrial fibrillation* is characterized by the ab-

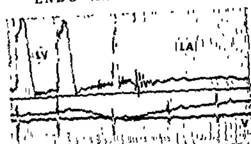


Fig. 4-208. Pure mitral stenosis with atrial fibrillation Pullback from the left ventricle LV to the left atrium LA. From above, endocardial pressure curve, endocardial unipolar lead, and lead 2. Film speed, 25 mm/sec. A sudden change in the endocardial tracings is seen when the catheter is pulled through the mitral valve in the left atrium LA Note the normal QS complex with negative T wave in the left ventricle LV. Irregular and polymorph "f" waves are seen in the left atrium LA

The *third vector (III)*, the most important of all, is due to the activation of the upper portions of the left septal mass its direction is [illegible] The last [illegible] portions [illegible] ducing a vector (IV) directed to the left and upwards, and pointing less posteriorly than the third

The activations of the apex and of the free left ventricular wall are usually masked by the more important forces of the left septal mass On the other hand, the electrical forces of the thin, free right ventricular wall, being early and unopposed by other forces, becomes *more manifest* (vector Ia) in LBBB

The following are the main unipolar *patterns* (Fig 4-210). *In the right cavities,* the QRS complexes are negative because the four vectors are pointing away from the electrode. The small initial positivity recorded over the free right ventricular wall is explained by the early forces of the free right ventricular wall (*vector Ia*) On the other hand, the similar positivity at the surface of the lower septal portions is explained by vector I, which is pointing in that direction.

In the *left ventricular cavity,* the pattern is RS the upstroke of R shows a notching, which represents vector I most of the upstroke of R and its peak correspond to vector II The broad slurred S wave is due to vectors III and IV, which are pointing away *from the ventricular cavity* The epicardial pattern of the free left ventricular wall is mainly of the rR type with a late plateau. The initial positivity represents vector I, which sometimes is manifested only by notching or slurring of the upstroke of R. The upstroke and the peak R correspond to vector II; the initial part of the following plateau is due to vector III; and the last part, to vector IV. *In the left atrium,* the pattern is similar to that just described, except for the initial negativity due to vector I

Incomplete Bundle Branch Block (BBB). For the recognition of incomplete BBB, one should mainly rely on the QRS pattern as related to ventricular activation, the duration of the QRS complex is far less relevant. Several

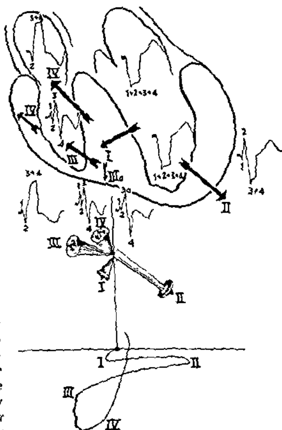


Fig. 4-209. Schematic representation of the most common unipolar endocardial and epicardial morphologies referred to the main vectors of ventricular activation in the presence of right bundle branch block (RBBB) Vectors I and II are similar to the normal ones. Vector III, activation of low and middle portions of the right septal mass in a direction opposite to the normal; vector IIIa, activation of the lower right septal mass, vector IV, late activation of the basal portions of the right septal mass and free right ventricular wall Note the secondary changes of the endocardial and epicardial ST and T waves.

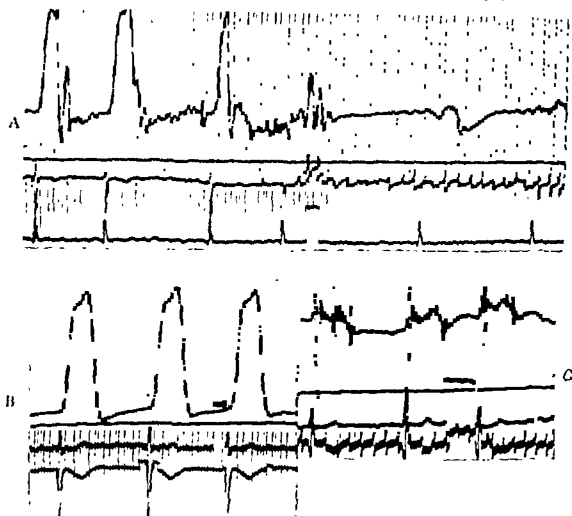


Fig. 4-207. Mitral stenosis with right ventricular hypertrophy and atrial flutter. A. Pullback from the right ventricle to the right atrium. From above: endocardial pressure curve, endocardial unipolar lead, and lead 2. A sudden change of pressure curve and endocardial electrocardiogram marks the crossing of the tricuspid valve, flutter waves appear as soon as the catheter is pulled in the atrium. B and C Pressure curve with lead 2 and endocardial unipolar lead, from the left ventricle and atrium, respectively In the left ventricle (B), the unipolar lead shows a QS complex with negative T waves and no evidence of atrial activity In the left atrium (C), prominent "F" waves with rapid intrinsicoid deflections are seen Film speeds. 25 mm/sec

right paraseptal regions on account of prevailing local forces (vector IIIa), which become more evident when right ventricular hypertrophy is present.

The last vector (IV) is responsible for the terminal portion of the positive plateau in the right atrium and in the right lateral epicardial leads, as well as for the S wave in the right ventricular cavity and in paraseptal epicardial leads (corresponding to the slurring of the S wave in V_5 to V_6). This slurring is explained by *slow activation of the middle and upper parts of* the right septal mass, the activation of the free right ventricular wall being normal

Complete Left Bundle Branch Block (LBBB). The ventricular activation in complete LBBB can also be visualized into four main vectors (Fig 4-210). The activation wave through the unblocked right bundle branch reaches the middle portion of the right septal surface, near the right anterior papillary muscle From here, it travels through the right septal mass, producing a *right-to-left vector (I)* pointing to the left, anteriorly, and downwards. Following this, the activation wave "jumps" the interseptal "barrier" to reach and activate in a slow way the low and middle portions of the left septal mass, generating a *vector (II)* pointing posteriorly and to the left, and with a horizontal or upward direction. Only in few vertical hearts does this vector point downwards



Fig. 4-208. Pure mitral stenosis with atrial fibrillation. Pullback from the left ventricle LV to the left atrium LA. *From above, endocardial pressure curve, endocardial unipolar lead, and lead 2.* Film speed: 25 mm/sec. A sudden change in the endocardial tracings is seen when the catheter is pulled through the mitral valve in the left atrium LA. Note the normal QS complex *with negative T wave in the left ventricle LV. Irregular and polymorph "f" waves are seen in the* left atrium LA.

The *third* vector (*III*), the most important of all, is due to the activation of the upper portions of the left septal *mass. Its direction is* to the left, *posteriorly, and upwards.* The last *portions to* be activated are the high portions of the free left ventricular wall, producing a *vector (IV)* directed *to the left and upwards,* and *pointing less posteriorly* than the third.

The activations of the apex and of the free left ventricular wall *are usually masked by the* more important *forces of the left septal mass.* On the *other hand, the* electrical forces of the *thin, free* right ventricular wall, being early and unopposed by other forces, *becomes more* manifest (vector Ia) *in* LBBB.

The *following are the main unipolar* patterns (*Fig.* 4-210). *In the right cavities,* the QRS complexes are negative because the *four vectors* are pointing away *from the electrode.* The small initial *positivity* recorded over the free right ventricular wall is explained by the early *forces of the free right ventricular wall (vector Ia).* On the other hand, *the similar* positivity at the surface of the lower septal portions is explained by vector I, which is pointing in that direction.

In the *left ventricular cavity,* the pattern is RS: the upstroke *of R shows a notching,* which represents vector I, most of the upstroke of R and *its* peak correspond to vector II. *The* broad, slurred S wave is due to *vectors III* and IV, which are *pointing away* from the ventricular *cavity. The epicardial* pattern of the free left ventricular wall *is mainly of the rR* type with a late plateau. The initial positivity represents vector I, *which sometimes* is manifested only by notching or slurring of the upstroke of R. The upstroke and the peak R correspond to vector II, the initial part of the *following* plateau *is* due *to* vector III; and the last part, to vector IV. *In the left atrium,* the pattern is similar to that just described, except for the initial negativity due to vector I.

Incomplete Bundle Branch Block (BBB). For the recognition of incomplete BBB, one *should mainly rely on the* QRS pattern as related to ventricular activation, *the duration* of the QRS complex is far less relevant. Several

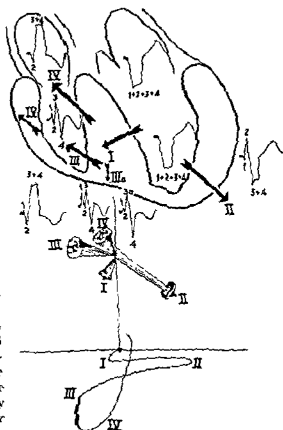


Fig. 4-209. Schematic *representation of the most common unipolar endocardial* and *epicardial* morphologies *referred to the main vectors of ventricular activation in the* presence of right bundle branch block (RBBB). Vectors I and II are similar to the *normal* ones. Vector III, activation of low *and* middle portions of the right septal mass *in a direction opposite to the normal, vector IIIa, activation* of the lower right septal *mass, vector IV, late activation of the basal portions of the right septal mass and free right ventricular* wall. Note the secondary changes *of the endocardial and* epicardial *ST and T waves.*

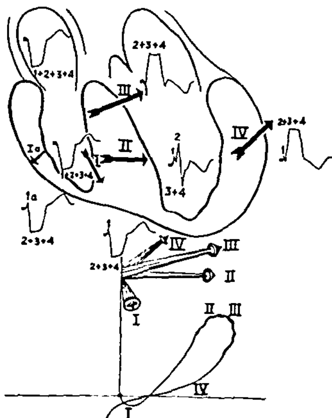


Fig. 4-210. Scheme as in Fig. 4-209 in the presence of the basal portions of the free left ventricular tion of the middle portion of the right septal mass, vector II, activation of low and middle portions of the left septal mass, vector III, activation of high portions of the left septal mass; vector IV, activation of left bundle branch block (LBBB) Vector I, activa-wall. Note the secondary changes of the endocardial and epicardial ST and T waves

clinical cardiologists accept a QRS duration of 0 12 sec as the dividing limit between complete and incomplete BBB, irrespective of the than 0.10 sec many exclude the possibility of pattern of QRS. Moreover, if QRS lasts less incomplete BBB, whatever the pattern

Experimental work and clinical observations convinced the authors of the shortcoming of these rules. Figures of 0 08 to 0 09 sec for QRS may represent slight degrees of incomplete BBB if the pattern thus indicates On the other hand, basing the interpretation on the process of ventricular activation, the diagnosis of incomplete BBB may be made even when the QRS duration is 0 12 to 0 13 sec This is also borne out by the fact that in the follow-up of a number of cases of "complete" BBB, a QRS of 0 13 sec may increase to 0 15 sec, indicating a degree of block which is more advanced than the previous "complete" one.

For the above reasons, it is better to rely on the QRS pattern, viewed according to the ventricular activation, as the only clue to the diagnosis of incomplete BBB. There are two degrees of incomplete BBB. *The first degree* is characterized by a small delay of the activation wave in one branch, which, however, still activates all of the homolateral ventricle. *The second degree* of incomplete BBB is characterized by a longer delay of the activation wave in one branch, so that some portions of the ventricle supplied by this branch are abnormally activated by the excitation wave coming from the other intact branch through the septal barrier. Complete BBB would be the transition from this degree of block to one where the entire ventricular mass is activated through one intact branch. From this, it becomes apparent that no classification of bundle branch blocks should be based only on the QRS duration.

In all the above-mentioned varieties of BBB one branch is supposed to be intact, so that, on one side, no delay of the activation wave should occur at any level. The possibility that this might not be true in every instance prompted the authors to investigate the experimental production of bilateral bundle branch block (BBBB). The following are some of the pertinent findings (Bisteni et al., 1960b). (1) When the degree of block is similar in both branches (slight, moderate, or marked), the QRS shows slight or no abnormality because the conduction to both ventricles is equally impaired, and there is no, or minimal, ventricular asynchronism In such a case the P-R interval becomes *longer* in proportion to the degree of bilateral block (2) When one block prevails over the other, there are changes in the P-R interval, in the QRS duration, and in the QRS pattern The P-R interval increases and its length depends on the delay of conduction in the branch with lesser degree of block. The QRS duration also increases, and its width is directly related to the difference between the degrees of block in the two branches. Finally, the QRS pattern is dependent upon the branch with the greater degree of block. (3) If both branches are completely blocked, an *idioventricular rhythm* appears, with no relation to atrial activity

A detailed description of right and left incomplete BBB escapes the scope of this presentation, only a brief outline will be made. The guiding principles for the recognition of the different degrees of BBB are based on endo-

cardial leads from both dogs and men, on intramural leads in animals, and on investigations on the Purkinje potentials in the dog's heart. In clinical cases, not infrequently the diagnosis of a minor degree of incomplete BBB can be suspected and proved only by the study of the time and mode of ventricular activation, as directly determined by recording intracavitary potentials

Incomplete Right Bundle Branch Block. In this condition, more than in any other, an exact positioning of the exploring intracavitary electrode is required because of the anatomic and electrical partition represented by the interventricular septum. In order to be sure of exploring that part of the right septal surface which is the first to be activated, the catheter should lie in the anterior and lower part of the right ventricular cavity Should the electrode be in the high and posterior part of this cavity, regions belonging anatomically to the left septum would be explored.

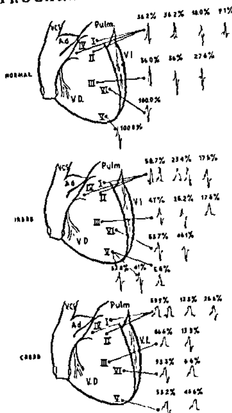


Fig 4-212. Scheme of the unipolar epicardial patterns in normal subject (NORMAL) and in incomplete (IRBBB) and complete (CRBBB) right bundle branch block (RBBB). *VCS*, superior vena cava; *Ad*, right atrium, *Pulm*, pulmonary artery; *V I.*, left ventricle; *V.D*, right ventricle Other references as in Fig. 4-211.

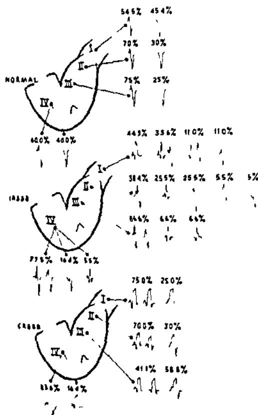


Fig 4-211 Scheme of the unipolar endocardial morphologies in normal subject (NORMAL) and in incomplete (IRBBB) and complete (CRBBB) right bundle branch block. The % refers to the incidence of the recorded patterns. The roman numerals indicate the different levels of the right ventricular cavity, from the inflow tract to the pulmonary artery

It has been mentioned that the intrinsic deflection of the portions having the earliest activation on the right septal surface occurs 0 010 to 0 015 sec after the activation of the left septal at its middle third Therefore, an intrinsic deflection of 0 02 sec or more at the level of the right lower and anterior septal surface is evidence of some degree of RBBB It is necessary to emphasize that this duration of the intrinsic deflection holds true only for these specified portions of the right septal surface, since higher and posterior portions belonging to the right septal mass are normally activated later.

The patterns most frequently recorded within the apical portion of the right ventricle (Fig 4-211) present a double positivity of the type

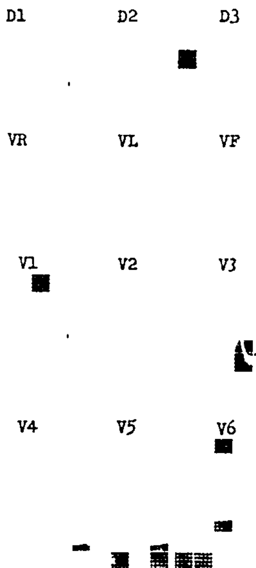


Fig. 4-213. Peripheral electrocardiogram of a patient with double mitral lesion and aortic insufficiency The tracing is suggestive of incomplete LBBB because of the absence of the Q wave in lead I (D1) and V_6 Film speed, 25 mm/sec

rsr's' or rsR'S', less frequently of the RS type with a slurred initial upstroke of R and an intrinsicoid deflection appearing later than 0 02 sec Over the trabecular zone of the right ventricle (Fig 4-212), the patterns are practically identical to those just described within the right ventricle. In higher regions of the right septal mass, the patterns differ only because of a smaller or absent S' while the R' increases and its intrinsicoid deflection is inscribed later

Incomplete Left Bundle Branch Block. An initial incomplete LBBB is revealed by the disappearance of the r wave within the apex of the right ventricle, indicating the disappearance of the normal asynchronism between the two opposite septal surfaces. With a greater degree of incomplete LBBB, the endocardial pattern in both ventricles will still be QS, but a bipolar lead across the lower part of the interventricular septum shows that the vector of septal depolarization is pointing from right to left (Figs. 4-213 through 4-215).

With an increasing degree of block, an initial positivity is recorded in the left ventricular cavity. However, this initial positivity will be significant only if the catheter lies in the cavity, since a small positivity can be normally recorded with the catheter in contact with the higher or lower left septal surface.

These varieties represent first or second degrees of incomplete LBBB. In the first degree *of LBBB, the initial normal positivity* disappears in the right precordial lead and the initial negativity disappears in the left. In the second degree of LBBB, there is slurring in both the upstroke and the downstroke of the R wave in left precordial leads.

In BBB, the recovery process (ST-T complex) undergoes the so-called "secondary" changes in a direction opposite to the area of the QRS complex. In *complete* BBB, the difference in activation time between the two septal surfaces may increase up to 0 07 to 0 08 sec in the human heart. According to Wilson, the sequence of activation determines in some degree the sequence of recovery, so that the more the activation process is altered, the more important the secondary changes of the recovery process are. In RBBB (Fig. 4-209), the general sequence of activation across the interventricular septum is from left to right and lasts from two to three times the normal duration. This in turn causes the recovery process to have the same left-to-right direction, and consequently the vector of recovery is pointing in the opposite direction This vector causes *positive T waves on the left of the septum* (left endocardial and epicardial leads) and *negative T waves on the right of the septum* (right endocardial and epicardial leads).

In *incomplete BBB*, similar secondary changes of the ST-T complex are present, but in a lesser degree.

Subsequent sections will deal with ventricular premature beats, W-P-W syndrome, and ventricular hypertrophy; all these conditions show severe secondary alterations of the recovery process.

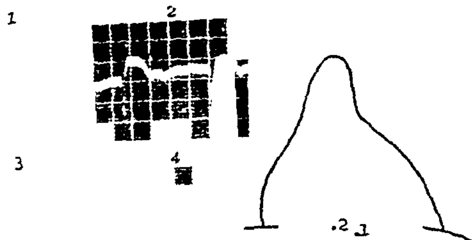


Fig. 4-214. Same patient as in Fig. 4-213. Unipolar endocardial leads recorded in the left ventricle (1) and in the right ventricle (2). In both ventricular cavities, the unipolar pattern is QS. A bipolar lead between 1 and 2 across the lower part of the interventricular septum shows a positive deflection, which suggests that the sense of septal activation is from right to left, 3. The bipolar lead between 1 and 2 with inverted polarity is also shown, 4.

Ventricular Premature Beats. It has been pointed out (Bisteni et al., 1960) that many of the so-called "ventricular premature beats" are actually supraventricular (atrial or nodal) premature beats with aberrant ventricular response, because of some delay in the progress of the activation wave through the right or left bundle branch. Depending on the degree of aberrancy, patterns of either incomplete or complete BBB are recorded.

In regard to true ventricular premature beats, the classical concept that left ventricular premature beats present a pattern similar to that of RBBB and that right ventricular premature beats are similar in pattern to LBBB still holds true. This means that the sequence of activation of a ventricular premature beat is similar to that taking place in a patient with block of the contralateral branch.

Right ventricular premature beats present a QS pattern with positive T wave in the right ventricular cavity (Fig. 4-216), and RS with negative T wave in the middle and lower portions of the left ventricular cavity. *Left ventricular premature beats* show a QS pattern with positive T wave in the left ventricle (Fig. 4-217A), and RS or rsR'S' pattern with negative T wave at lower levels of the right ventricular cavity.

Thus the pattern of the intracavitary tracing is the same (QS with secondary positive T waves) irrespective of the ventricle in which the premature beat originates.



Fig. 4-215. Same patient as in Fig. 4-213. Chest x-ray showing the two catheter-electrodes within the two ventricles.

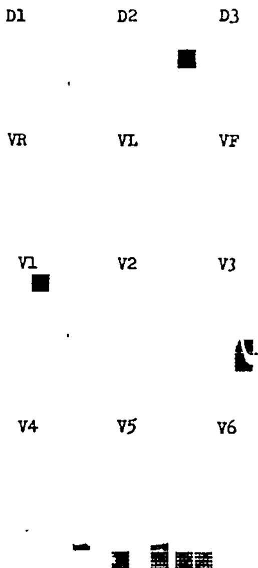


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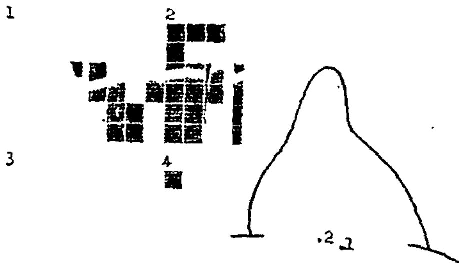


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Right ventricular premature beats present a QS pattern with positive T wave in the right ventricular cavity (Fig 4-216), and RS with negative T wave in the middle and lower portions of the left ventricular cavity. *Left ventricular premature beats* show a QS pattern with positive T wave in the left ventricle (Fig 4-217A), and RS or rsR'S' pattern with negative T wave at lower levels of the right ventricular cavity

Thus, the pattern of the intracavitary tracing is the same (QS with secondary positive T waves) irrespective of the ventricle in which the premature beat originates



Fig 4-215. Same patient as in Fig. 4-213 Chest x-ray showing the two catheter-electrodes within the two ventricles.



Fig. 4-216. Right ventricular premature beat. From above: right ventricular pressure, endocardial unipolar lead from the same ventricle, and lead 2 Film speed, 25 mm/sec The third beat is a right ventricular premature beat showing the endocardial morphology of widened QS with secondary ST and T changes

It is important to remember that the ventricular complex always shows an initial positivity at the epicardial surface of the ventricle opposite to the one where the premature beat originates. Therefore, if an initial negative wave is recorded from these areas, it means that there has been myocardial necrosis The authors' laboratory has demonstrated the value of ventricular premature beats for the recognition of myocardial infarctions, if the evidence of necrosis is absent in the complexes of sinus origin

It is the opinion of the authors that ventricular premature beats may also help in the diagnosis of atrial and ventricular hypertrophy Definite conclusions, however, are still unwarranted; more knowledge concerning the sequence of ventricular activation is needed.

Ventricular premature beats are easily produced during right or left heart catheterization through stimulation of the ventricular endocardium by the exploring electrode. These premature beats disappear by rotation or withdrawal of the catheter. If the catheter tip presses against the ventricular or atrial endocardium, a monophasic wave of injury may appear. This wave is recorded only in the endocardial electrocardiogram of the explored cavity and is not accompanied by S-T deviation in simultaneous standard or precordial leads or in endocardial leads from other cardiac chambers (Fig. 4-217B). Additional evidence indicates that the endocardial injury pattern is due to a minimal localized injury, which disappears on withdrawal of the catheter.

The sensitivity of the ventricular endocardium to mechanical stimulation by the catheter is of practical importance in Ebstein's disease In this disease, pressure of the catheter against the right "atrial" wall is accompanied by a ventricular monophasic wave; this indicates the existence of ventricular musculature above the tricuspid valve, a malformation which is characteristic of this anomaly.

Wolff-Parkinson-White (W-P-W) Syndrome. In order to understand the various patterns of the W-P-W syndrome, reference should be made to the sequence of ventricular activation. It is convenient to classify cases of W-P-W syndrome (A and B) according to the patterns of standard and unipolar leads (Rosenbaum et al)

TYPE A The ÂQRS is generally located around +90° in the frontal plane, and predominantly positive areas of QRS are recorded in all precordial leads. The initial slurring of QRS (delta wave) is usually positive in leads 2, 3, VF, and V_1 to V_6 Experimentally, similar patterns are reproduced by stimulating *the posterior and superior portions of the interventricular septum*, from either the right or the left septal mass (Fig 4-218). The mean spatial vector of ventricular activation is directed from above downwards, from back to front, and slightly to the left (ÂQRS around +90° in the frontal plane and positive deflections from V_1 to V_6).

This form of activation determines a wave of initial positivity in both ventricular cavities. In the right ventricle (Fig 4-219), the main unipolar patterns may be summarized as follows: in the high portions of the outflow tract near the pulmonary valve, QS with negative delta wave and secondary positive T wave;

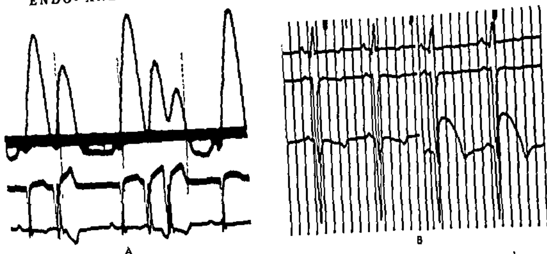


Fig 4-217 A Left ventricular premature beat. From above left ventricular pressure, endocardial unipolar lead from the same ventricle, and lead 2 Film speed, 25 mm/sec. The second, fourth, and fifth beats are left ventricular premature beats Note the widened endocardial QS with secondary ST and T changes B Ventricular injury wave produced in a dog From above lead 2, and unipolar leads from the right and left ventricular cavities, respectively. Film speed, 100 mm/sec. The tracings were taken before (left of the figure) and after (right of the figure) an injury (incomplete monophasic wave) was produced by pressing the tip of the exploring electrode against the endocardial surface of the left ventricle The injury wave is recorded only from the electrode inside the left ventricle, no changes are seen in either the unipolar lead of the right ventricle or in lead 2.

near the tricuspid valve, Rs with positive delta wave and negative T wave

This type of the syndrome shows some resemblance to RBBB, particularly in the precordial leads The sequence of ventricular activation, however, is different in the two conditions because the right ventricle is activated late in RBBB while it is activated early in the W-P-W ("preexcitation") syndrome In addition, if both anomalies are experimentally produced at the same time, the records tend to become normal in consequence of cancellation effects

TYPE B The AQRS is usually deviated to the left (around −30°) in the frontal plane, while predominantly negative deflections with negative delta wave are recorded in leads 2, 3, VF, and V_1 to V_4

The sequence of ventricular activation is in many ways similar to that described in incomplete LBBB, and sometimes it is difficult to differentiate these two abnormalities It should be noted, however, that although the sequence of activation is the same in the two instances, in incomplete LBBB the left ventricle is activated with a delay, while in this type of W-P-W syndrome, it is activated at its normal time and the right ventricle is activated in advance It appears that the earliest regions to become activated are the middle and posterior portions of the right septal mass The mean spatial vector of ventricular activation can be visualized as pointing to the left, upwards, and to the back (predominantly negative deflections in leads 2, 3, VF, and right precordial)

In the right ventricular cavity, the following unipolar patterns (Fig 4-220) are recorded: at the apex, RS or rS with positive delta wave and secondary negative T wave, in high portions of the outflow tract, Rs with positive delta wave and negative T wave, and near the tricuspid valve, QS with negative delta wave and positive T wave

In view of the similarity of ventricular activation with that of incomplete LBBB, a pattern consisting of RS with positive delta wave and negative T wave is expected in the left ventricular cavity near the apex Therefore, almost identical unipolar patterns are recorded at lower levels of the left ventricle in both types of the W-P-W syndrome.

There probably are some other types of W-P-W syndrome, as yet not fully identified, which present some characteristics of both type

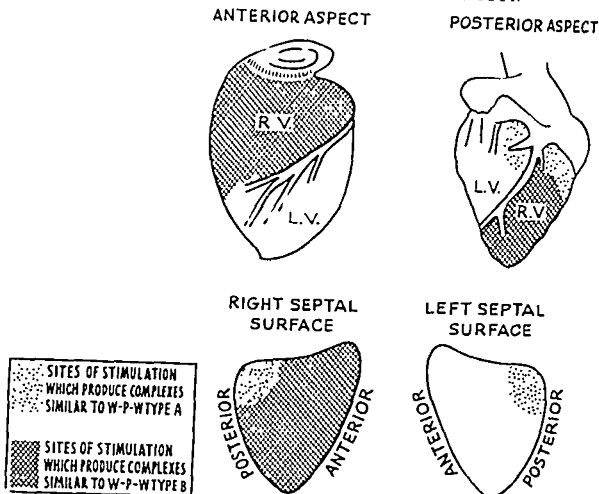


Fig. 4-218. Schematic representation of the sites of stimulation producing complexes similar to type A (pointed areas) and type B (shadowed areas) of Wolff-Parkinson-White (W-P-W) syndrome.

A and type B. For instance, there are cases with AQRS deviated to the left, which at the same time resemble type A in the precordial leads These cases could well be called type C

Right Ventricular Hypertrophy (RVH). Many subjects with RVH also present some degree of RBBB, as determined by endocardial electrocardiography. In pure RVH, the endocardial and epicardial patterns (Fig 4-221) are modified by the increased electromotive forces of the hypertrophied free right ventricular wall and right septal mass (vectors IIIa, IIIb, and IV).

The negative T wave in the left ventricular cavity (Fig. 4-221) suggests that the recovery forces of the hypertrophied right ventricle are not important enough to counterbalance those of the free left ventricular wall In many cases of marked RVH with systolic overload of the right ventricle, the T wave was negative in the right ventricular and atrial cavities and negative (ischemic type) over most of the anterior precordial leads, with a pattern suggestive of right ventricular and right septal hypertrophy. As tentative explanation of these findings, it might be admitted that the most important forces of recovery are across the free right ventricular wall, not across the interventricular septum, as in BBB. This would be consistent with the authors' experience, because primary T-wave changes over the right precordial leads have been found only in subjects with the highest degree of systolic overload of the right ventricle and are probably the electrocardiographic expression of subepicardial ischemia. In other cases of systolic overload of the right ventricle, where the T waves are positive over the right precordial leads, the overload is of a lesser degree and the T waves probably represent subendocardial ischemia of the right ventricle

Left Ventricular Hypertrophy (LVH). The sequence of ventricular activation in LVH proceeds as normally, unless some degree of LBBB is present Generally the electromotive forces across the free left ventricular wall are in-

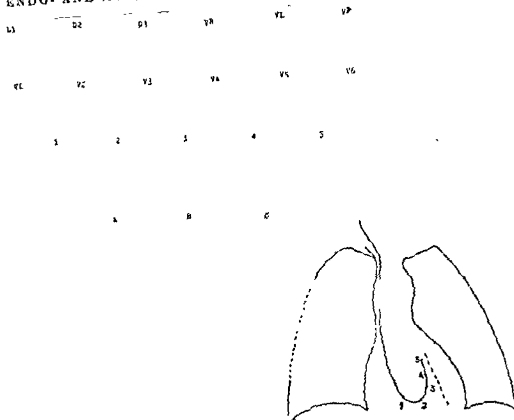


Fig 4-219 *Type A of W-P-W syndrome. Peripheral electrocardiogram* at the top of the figure. Unipolar endocardial patterns *obtained in* the right ventricle (points 1 to 5) and in the *right* atrium (*A, high, B, middle; C, low level*) *Note the Rs complex* with positive delta wave and negative T waves near the tricuspid valve *Film speeds, 25 mm/sec*

creased (*vectors II and III*, Fig 4-221B) The forces due to the left septal *mass* (vector I) may also be increased, hypertrophy of the left septum *is suggested* when a tall positivity is recorded in the right epicardial leads, simultaneously with a deep negativity in the left epicardial leads.

In the left ventricular *cavity*, a *QS* complex of increase voltage and *usually* a positive T wave are found (Fig 4-222) Generally this pattern is associated with an advanced degree of systolic overload of the left ventricle and with negative T waves of the secondary type in the left precordial leads The reason for these *changes* of the T wave is that the recovery process (AT) is modified because of increased depolarization time between endocardial and epicardial surfaces of the free left ventricular wall The T vector points now toward the left ventricular cavity, causing positivity of the T wave within this chamber and negativity of this wave outside the chamber.

In other subjects, the T wave may remain *positive in* the left epicardial leads *and negative within* the left ventricle, even in the presence of LVH. This often *corresponds to* diseases associated with diastolic *overload* of the left ventricle It should be *remembered*, however, that in the presence of even a *minor* degree of LBBB, the T wave presents secondary *changes*, and thus the pattern of diastolic overload of the left ventricle *cannot* be diagnosed from the shape of the T wave.

MYOCARDIAL INFARCTION

Figure 4-223 schematizes the *free* left ventricular wall, which *is supposed* to be electrically partitioned into two parts. Normally, in the electrical endocardium (*A*, points 1 to 4) the unipolar pattern is *QS* with negative T wave, as in the cavity, while in the electrical

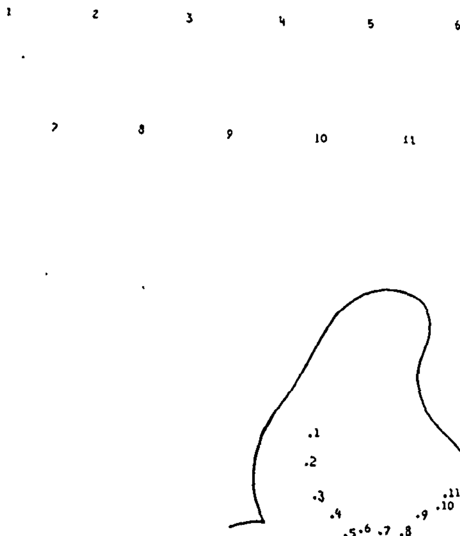


Fig. 4-220. Type B of W-P-W syndrome. Unipolar endocardial patterns obtained in the right atrium (points .1 to 3) and in the right ventricle (points 4 to .11). Near the tricuspid valve, QS with negative delta wave and positive T wave are recorded At the apex of the right ventricle, rS or RS with positive delta wave and negative T wave are registered Film speeds, 25 mm/sec.

epicardium (A, points 5 to 7), an initial positivity is recorded, which becomes more important as the electrode is moved toward the outer layers. In *transmural necrosis* (B), the endocardial pattern is transmitted to any epicardial lead facing the necrosis. On the other hand, if *the infarction is limited to the electrical endocardium* (C), *the intact epicardium will give rise to its normal potentials and thus completely mask such an infarction* Should the necrosis extend partly *to the epicardial layers* (D), a negativity is recorded, which is dependent on the depth and width of the epicardial necrosis. Finally, when the infarction is localized *only in the electrical epicardium* (E), its electrical forces disappear and the epicardial pattern will be the same as the endocardial. In such cases, the unipolar pattern is identical to that of a transmural infarction (B), which is therefore indistinguishable from an infarct involving solely the electrical epicardium (E).

Detailed pathologic correlations and greater knowledge of the activation process have enabled the authors better to localize the necrotic zones (Sodi-Pallares et al., 1960).

In the absence of BBB (Fig. 4-224), an *infarction of the middle third of the septum* (A) causes the disappearance of the septal forces responsible for the normal first septal vector and the consequent disappearance of r in the right epicardial lead and of q in the left epicardial lead. If the infarction is *in the lower third of the septum* (B), only its forces will disappear, and a QS pattern with negative T wave is recorded over the lower anteroseptal regions corresponding to V_3 to V_4. With the

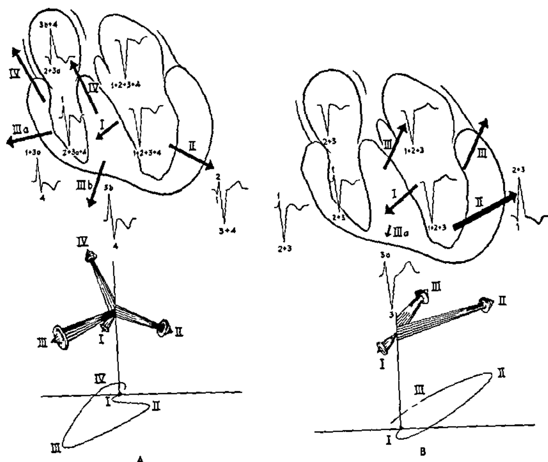


Fig. 4-221. A, Schematic representation of unipolar endocardial and epicardial unipolar patterns referred to the main vectors of ventricular activation in the presence of right ventricular hypertrophy (Same references as in previous figures) Vectors I and II are similar to the normal ones, vector III, resultant of vector IIIa (activation of the free right ventricular wall) and vector IIIb (activation of the low right septal mass), vector IV, resultant activation vector of basal portions of the free right ventricular wall and right septum Note the secondary changes of the endocardial and epicardial ST and T waves B Scheme as in A, in the presence of left ventricular hypertrophy Predominance of the vectors of left ventricular activation (vectors I, II, and III) is shown Vector IIIa, activation of the lower left septal mass Note the secondary changes of the endocardial and epicardial ST and T waves

necrosis involving *both the middle and lower thirds of the septum* (C), the result is a combination of the two previous conditions If the necrosis, as in B, leaves viable some subepicardial portions (D), a late r is recorded over these areas. On the other hand, if the necrosis (as in C) extends more toward the free right ventricular wall, leaving some lower septal parts still excitable (E), an early R is recorded over these areas, and a late R over the former areas With an infarction extending to *both free ventricular walls and up to the middle* (F) *or upper third of the septum* (G), a QS pattern and a negative T wave are recorded over an extensive anterolateral area of the epicardium and over the entire precordium.

In the presence of RBBB, the necrosis can be localized, if the activation process is kept in mind In Fig. 4-225 are schematized the various possibilities In A are represented for reference the unipolar endocardial and epicardial patterns in uncomplicated RBBB In *isolated necrosis of the middle third of the left septal mass* (B), an initial negativity is recorded in the right, and an initial positivity (disappearance of the normal q) in the left

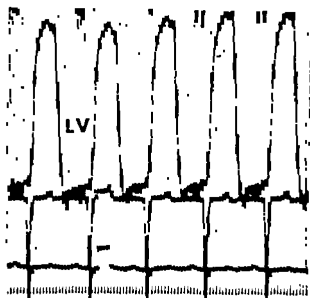


Fig. 4-222. Isolated left ventricular hypertrophy. From above. left ventricular pressure, unipolar lead from the same ventricle, and lead 2 Film speed, 25 mm/sec. The calibration is presented after the second beat Note the increased voltage of the QS complex with positive endocardial T waves

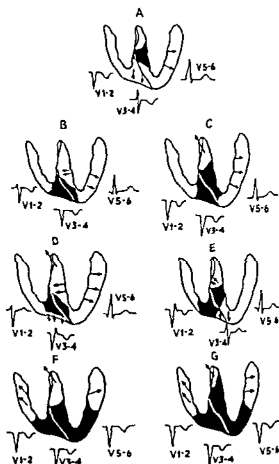


Fig. 4-224. Scheme of the various locations of myocardial necrosis with normal sequence of ventricular activation See text

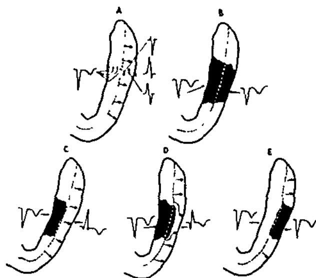


Fig. 4-223. Schemes of the free left ventricular wall in normal conditions and with different locations of necrosis. The electrical endocardial surface is represented by the dotted line between points 4 and 5 A Normal condition. In points 1 to 4, QS deflections are recorded because of the closed polarized fronts of activation, as illustrated in Fig. 4-205. In points 5 to 7 an initial positivity of the ventricular complex is registered. B. Transmural infarction C Subendocardial infarction that does not reach the electrical endocardial surface. D. Subendocardial infarction that extends behind the electrical endocardial surface. E. Subepicardial infarction that reaches the electrical endocardial surface and determines a pattern similar to one with a transmural infarction.

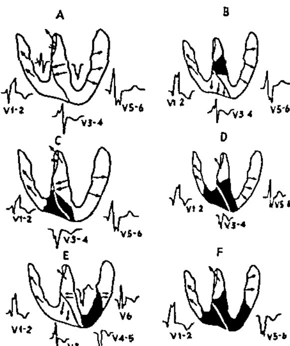


Fig. 4-225. Scheme of the various locations of myocardial necrosis in the presence of RBBB See text

epicardial and precordial leads An infarction *in the lower septal mass* (C) is revealed by a *QS with slurred* descending branch and negative T wave over the anteroseptal regions. If the infarction extends also to the *middle third of the septum* (D), the result will be a combination of the *two previously* considered situations With a *transmural necrosis of the free left ventricular wall* (E), the signs of infarction (deep *initial negativity and primary* ST and T-wave changes) will be evident over this area, as well as a nearby area (V_6). Last, when the necrosis occupies *the lower two-thirds of the septum with extension to both adjacent free ventricular walls* (F), a combination of the last two conditions is obtained

In LBBB, the electrocardiographic diagnosis of necrosis most often can be made through knowledge of the sequence of activation and on the basis of the unipolar endocardial and epicardial patterns in LBBB Figure 4-226 is a schematic representation of the most common condition In A are represented for reference the various patterns in uncomplicated *LBBB* With a *transmural necrosis of the free left ventricular wall* (B), the endocardial pattern will be transmitted to an electrode facing the area If the necrosis is *in the lower third of the septum* (C), an initial negativity is inscribed both within and without the left ventricle In D is illustrated a combination of the two previous conditions. The qRs (R wave wide and slurred) with negative T wave over the necrotic area is interpreted as follows. the q wave is related to the necrosis of the lower septal mass, the s wave reflects the endocardial negativity through the dead zone of the *free left* ventricular wall, while the R wave is due to the forces of the intact medial and basal portions of the septum and left ventricle Should the infarction extend *higher in the interventricular septum* (E) than in the last case, qRs with negative T wave, not characteristic of LBBB, will be recorded at the two opposite surfaces of the infarction, and higher epicardial regions must be explored to find the typical patterns of LBBB. When *massive infarction of the septum* is present (F), wide and slurred QS with *negative* T wave is recorded over an extensive anterolateral area, as first described by Wilson, only high and posterior regions will yield the characteristic pattern of LBBB Finally, when the *necrosis occupies the lower septal mass (corresponding to the right septum) with extension to both free ventricular walls* (G), patterns simulating RBBB are recorded over *the necrotic area* because of the transmission of intraseptal and left ventricular endocardial pattern through the necrotic tissue Exploring high and posterior regions of the left ventricle, however, will clarify the diagnosis of LBBB and reveal the false pattern of RBBB

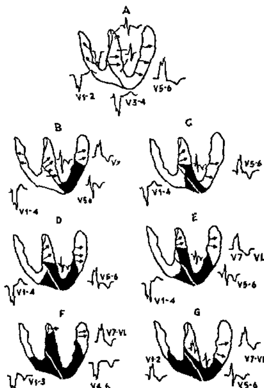


Fig 4-226 Scheme of the various locations of myocardial necrosis in the presence of LBBB. See text.

MYOCARDIAL INJURY AND ISCHEMIA

Studies of endocardial electrocardiography have greatly contributed to the understanding of the recovery process of the ventricles in normal and pathologic conditions (ST-T complex) Although few observations have been made in man, these parallel earlier experimental findings in the dog heart and permit certain generalizations.

Only the so-called "primary" ST-T changes observed in coronary heart disease will be considered here

Subepicardial Injury and Ischemia. These electrocardiographic diagnoses are made in the presence of positive ST with upward convexity (injury) and negative, symmetric T wave (ischemia) in leads facing the damaged area

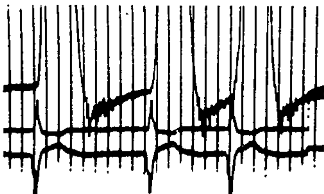


Fig. 4-227. Subendocardial injury. *From above:* left ventricular pressure, lead 2, and unipolar lead from the left ventricular cavity. Film speed, 100/sec. The calibration is shown at the end of the tracing. The intracavitary lead presents a positive ST displacement with upward convexity, which is opposite to the ST changes of the peripheral lead.

A B C

Fig. 4-228. Subendocardial ischemia. Unipolar endocardial morphologies recorded at two different levels of the right ventricle (A and B). In C, the catheter electrode was in the same place as in B while the patient experienced an acute attack of angina pectoris. Note the increase of voltage of the negative endocardial T wave. In the authors' interpretation, the electrode inside the right ventricle is facing the endocardial surface of the left ventricle. Film speeds, 25 mm/sec.

Mirror image (negative ST with upward concavity and positive, symmetric T waves) is found in opposite peripheral and endocardial leads.

Subendocardial Injury and Ischemia. These are usually recognized by negative ST with upward concavity (injury), and by positive, symmetric T wave (ischemia) in those epicardial leads located at the same level as the damaged area. In subendocardial injury of the left ventricle, a unipolar lead from this cavity shows a positive ST with upward convexity (Fig 4-227). In subendocardial ischemia, an endocardial lead records a deeply negative, symmetric T wave (Fig 4-228).

Figure 4-228 refers to a patient with chronic coronary insufficiency who presented a normal peripheral electrocardiogram at rest. During catheterization, while the endocardial tracing was being taken, the patient experienced a severe attack of precordial pain. During the attack, the intracavitary electrocardiogram showed a considerable increase of negative T wave over the control tracing, while the R wave remained of the same height.

16

Rheometry and rheography

DIOGENE FURBETTA

RHEOMETRY

Rheometry is the tracing of the changes of electric resistance of the body This method of investigation employs a particular instrument, the *rheometer*, which introduces a continuous or alternating current of minimal intensity into the body, the latter, as any conductor, has a certain electric resistance which varies according to the position of certain organs and their content of blood

Physical Principles The electric resistance of a conductor is represented by the ratio between the difference of potential of a current V applied to it and the intensity of the current i which flows in it (Ohm's law, $R = V/i$) The unit of measure is the *ohm*, which is defined as the resistance for a current of one volt and an intensity of one ampere. The resistance depends upon the size of the conductor (ratio between the length l and the thickness s) and upon a coefficient based on its physical nature (resistivity of the conductor in accordance to the second Ohm's law, $R = \rho l/s$) The terms *conductance* and *conductivity* indicate values that are inversely proportional to the resistance and the resistivity When a difference of potential is applied to a condenser (two conductors separated by a dielectric), another property should be considered, the electric capacity C This may be calculated by the ratio between the charge Q assumed by the condenser and the voltage V applied to it ($C = Q/V$) The unit of measure is the farad ($Q = 1$ coulomb, $V = 1$ volt). The third electric property of the conductors, i e , conductance, never appears in organic conductors, according to Stacy et al The term *impedance* indicates the changes of resistance or of capacity undergone by an alternating current which flows through an organic conductor, in such a circumstance, the current shows a diminution of intensity of the resistance and, on account of a capacitive effect, an anticipation of the waves (phase shift) and a change of pattern of the waves. For continuous currents, another phenomenon should also be considered, if metal electrodes are employed, higher values of resistance occur (polarization).

Biologic Systems as Electric Conductors. The human body may be considered as an envelope (skin and mucosa) containing an aqueous solution of electrolytes in which cells and undissociated particles are suspended, therefore, like any other electrolytic conductor, it may be traversed by an electric current The cellular membranes and the epidermis are the anatomic structures that offer the highest resistivity; as a consequence, a weak current applied to the skin cannot pass through. This obstacle can be overcome by employing stronger currents or by increasing the frequency of the oscillations (alternating current) When a current is applied to an isolated tissue (tissue deprived of the skin), it flows through the intercellular spaces, avoiding the cellular structures. The resistance and the capacity of the organ conductors vary, depending upon (1) the type of current and the mode of its application, (2) the anatomic, physicochemical, and functional characteristics of the tissues. When the method of measurement has been standardized, the changes of resistance depend only upon the anatomic and functional characteristics of the tissues and the composition of the organic fluids. The measurement of electric resistances of biologic systems is of use both in biology and in medicine Instruments employing electric

currents as a stimulus (neuromuscular diagnosis, electroshock, cardiac defibrillation) are based on *rheometry*. In studies of lesions induced by electricity, also, the electric resistance of the body must be known. Finally, rheometry is basic for studies in the cardiovascular field (rheography and rheocardiography), as well as for electrocardiography. Three practical methods have been devised and experimented with in biology and in medicine.

1. Methods of *direct measure*. the current is induced at a constant potential and a microamperometer records the intensity at the exit According to Ohm's law, the resistance is derived from their ratio. Instruments based on this principle are those devised by Regelsberger, Heinicke, and Furbetta et al.

2. Methods based *upon comparison with a known resistance*, regulated by means of a Wheatstone bridge The rheograph and the psychogalvanometer, as well as many other instruments used in biology for the measurement of the electric resistance of tissues and fluids, are based on this principle The use of alternating currents in this system permits the measurement of the electric capacity

3 *Oscilloscopic control* of the changes of the alternating currents. By employing sinusoidal waves, conductivity may be measured according to the degree of phase shift of the wave (Rosendal), by employing square waves, it may be measured according to the bending showed by the sides of the plateau (Teorell, Furbetta et al , 1959)

Results. Only a brief summary of the most important results is given here, more detailed description can be found in the monographs of Strohl. Regelsberger. Rosendal, Freiberger. and in the publications of Schwann and Kay, Berger and van Milvan, Horton and van Ravenswaay

When a continuous current is applied to a cutaneous surface, progressively increasing values of the resistance may be observed. until a stable value is reached, such a behavior is attributed to the polarization of the electrodes. unless impolarizable electrodes are used The obtained values are chiefly dependent upon the anatomicofunctional characteristics of the skin i.e , perspiration (Regelsberger) and thickness of the epidermis (Rosendal). Using a special technique, Krause et al. were able to obtain values that were chiefly proportional to the water content of the subcutaneous tissue: independently from perspiration, the resistance would decrease in edema, and in states of retention of water and salt.

Clinical investigations on the electric resistance of the human skin show wide variations during the day (daily curves or *electrodermatogram* of Regelsberger), with variations in both physiologic and pathologic conditions, depending upon the fluctuations of the autonomic tonus which modifies the amount of perspiration of the skin.

Abnormal data have been obtained in diseases of the heart, liver, central nervous system, endocrine glands, etc. Observations of Heinicke and Heidelmann have shown a marked increase of the skin resistance in the lower extremities in dystrophies caused by peripheral vascular diseases and a decrease of resistance following sympathectomy (Montorsi et al). One should further mention the studies devoted to the psychogalvanic reflex of the skin under psychogenic and sensorial stimulation, and the possible use of these results in questioning suspect individuals (so-called "lie detector")

From a cardiologic point of view, study of the electric resistances using a continuous current is of little use, because of great variations, the data are difficult to interpret (Furbetta et al , 1959).

The *psychogalvanometer* may be employed in cardiology for the evaluation of the emotional state of the patient Using alternating currents, the electric resistance is inversely proportional to the capacity, and decreases with the increase of the employed frequency Special techniques (Rosendal) permit the evaluation of the behavior of the resistance of the skin alone, of the skin plus the underlying tissues, or of the deep tissues alone, in any area. The values obtained show less variability than those obtained by employing a continuous current.

In the clinical field, a lowering of the electric resistance may be observed in *hyperthyroidism, after physical exertion* (Rutenfranz and Wenzel), and in *edema*, increased resistance is found in myxedema and in muscular paralysis (Rosendal) Subsequent work, based upon the phase shift of the waves of an alternating current, confirms such findings (Barnett, Brazier, Krepsky, Farzaneh; Rosendal). According to the author's experience, alternating currents of 10 to 50 kc/sec may be successfully employed in the clinical fields; the obtained values are significant and reproducible

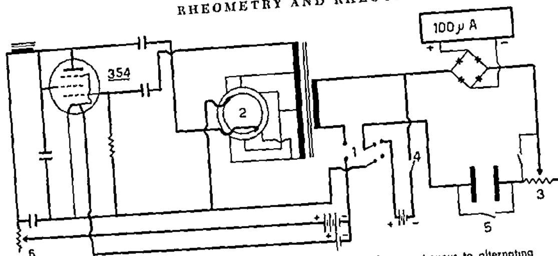


Fig. 4-229. Scheme of the rheometer of Furbetta et al 1, switch from continuous to alternating current, 2, frequency switch, 3, potentiometer, 4, switch for excluding battery, 5, switch for measurement circuit, 6, potentiometer

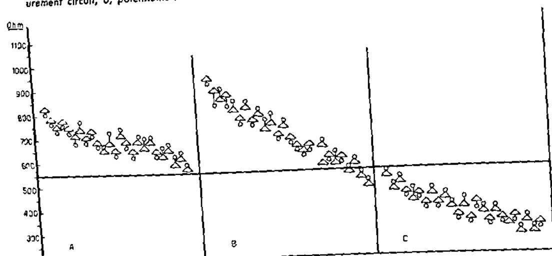


Fig. 4-230. Values of the electric resistance measured at the lower extremities (o = right, Δ = left) A Normal subjects B Nonedematous patients with cardiac disease. C. Edematous patients with cardiac disease

The Rheometer in Clinical Rheometry The apparatus (rheometer of Furbetta et al , Fig 4-229) consists of (1) a generator of current, which a transformer switches from a continuous to an alternating current of different frequencies, (2) two wire cables, terminating in two electrodes to be applied on the skin, and (3) a microamperometer, which reveals how much of the inducted current is actually flowing through the body Before performing the test, a shunt is established by means of a switch between the two wires, and the apparatus is balanced by bringing the needle of the amperometer to 100. After the two wires have been connected to the patient, the value recorded by the needle (percentage of the former value) may be reckoned in ohms by the use of calibration curves The electric capacity cannot be measured through use of this instrument, nor can the values of the phase shift of the sinusoidal current or of the deformation of the square waves (Teorell, Furbetta et al , 1959). The most important data are obtained by employing an alternating current at 50 kc/sec and by applying the electrodes on the extremities The study of the changes of electric resistance has been shown to be of great interest and of clinical utility in cardiology Figure 4-230 shows the values of the electric resistance at the lower extremities, in normal subjects and in edema-

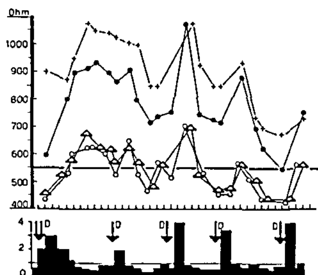


Fig. 4-231. Subject in heart failure followed for over 1 month. *Above*: values of the resistance at the upper (o = right; + = left) and lower extremities (o right, Δ = left). *Below*: amount of daily diuresis in 1,000 ml D marks the administration of mercurial diuretics.

tous and nonedematous patients with cardiac disease. In normal persons, the values of electric resistance were never found below 550 ohms, in edematous patients with cardiac disease, the values were always below 550. Among nonedematous patients with cardiac disease, some show normal values, others present lower values and should be considered as being in a preedematous condition (state of latent edema), even if the clinical findings are negative This is confirmed by the almost constant appearance of clinically apparent edema in the follow-up of these patients, if they are not properly treated. When the amount of extracellular fluid could be determined, and was compared with the decrease of electric resistance, a constant and significant fluid retention was demonstrated. The rheometric study of the decompensated edematous patient with cardiac disease treated with digitalis and diuretics may thus give useful information about the changes of the water and salt metabolism. By using such a method, one may easily follow changes in the total amount of the body fluids, as well as changes in their distribution (displacement of the fluids on account of gravitational influence). The observed variations are proportional to the degree of subcutaneous edema and correlated with the amount of diuresis (Fig. 4-231).

The above data, together with those observed in other physiologic and pathologic conditions, indicate that the basic cause of all changes of resistance is a difference in the quantity of water and electrolytes present in the body region to which the current is applied. The high-frequency alternating current penetrates deeply into the tissues and flows only through the interstitial fluids, which are good conductors because of the presence of dissociated salts, therefore, the fluids, according to their concentration and quantity, are the basic determinant of the values of electric conductivity (Fig 4-232)

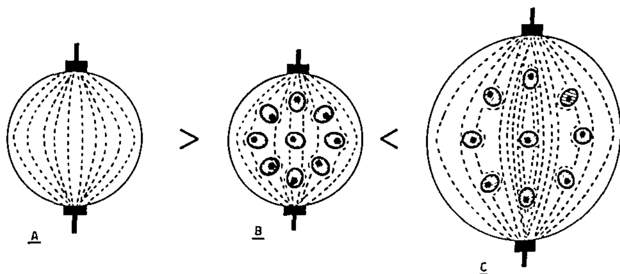


Fig. 4-232. Electric conductivity of a conductor. A. Decreased conductivity due to the presence of nonconducting structures within the conductor. B. Increased conductivity due to the increase of the conductive volume. C. Schematic representation of the electric conductivity of the tissues in function of the number of nonconductive cells B, and of the interstitial, good conductor fluid C.

Electric Resistance of the Organic Fluids. This resistance, measured with alternating currents of very low and medium frequency (Sundermann), depends upon the total electrolyte concentration of the examined fluid This measurement may then be employed in the study of the water and salt metabolism, because even if it does not yield data related to the quantity of the individual salts, it nevertheless gives their total value regarding the dissociated and "electrolytically active" salts

Curves of the Electric Conductibility of the Blood. White devised an electric method for the measure of cardiac output, based upon the principle of the dilution of indicators into the blood A catheter containing two wire conductors of platinum is introduced into an artery, the wires are connected with a Wheatstone bridge. Any variation of the electric conductivity of the blood may thus be measured Venous infusion of a saline solution increases conductivity, such an increase, recorded at the tip of the catheter and transmitted to the bridge, is then registered on a film. The tracing resembles the curve obtained by means of dye dilution, and permits calculation of cardiac output This method has been used with good results by Halt in animals, and has been applied by Booth et al in man to the study of cardiovascular shunts Instead of saline solution, Goodwin and Sapirstein employ autogenous plasma, which, having a different conductivity from the blood, determines in the same way the appearance of a curve that may be used in determining the cardiac output

RHEOGRAPHY

Rheography is based on the study of the instantaneous variations of resistance of the human body to the passage of electric currents The tracings recorded are named *rheograms* (RG) if they result from sections outside the heart, and *rheocardiograms* (RCG) if they are recorded on the precordium

The intensity of the current passing through the human body depends upon the resistance of the different tissues because it flows preferably through tissues having less resistance and better conductivity The blood is the best conductor of all tissues, followed by the lungs, the muscles, the heart, and the liver Because of the presence of two moving masses, the blood and the air of the respiratory system, the conductivity of the human body is not constant If the patient is in apnea, the instantaneous variations of resistance depend only upon changes of cardiovascular function. In the rheographic method, the variations of resistance are determined through the use of an alternating current of high frequency and low intensity.

History and Apparatus. Cremer (1907) was the first to obtain a tracing due to the variations of capacity of a conductor in relation with the cardiac activity. He did so by suspending a frog heart between the plates of a condenser. Several authors became interested in this method after 1932, and different types of apparatus were developed (Atzler et al., Furbetta et al , 1955, 1956; Donzelot et al.).

The *impedance plethysmograph of Nyboer* (1940–1950) is the most similar to a rheograph Nyboer's apparatus was built for measuring the local changes of blood flow through variations of impedance It reveals the instantaneous variations of electric impedance of the human body, that is, ohmic resistance, inductive reactance, and capacity reactance

Holzer et al (1945) built a similar apparatus, called a *rheocardiograph.* The instrument (Fig 4-233) consists of a generator of alternating current (frequency, 15 to 16 kc/sec, intensity, 15 to 20 ma) and a Wheatstone bridge with compensation of resistance and capacity The instantaneous variations of resistance are rectified, amplified, and registered by the galvanometer of an ECG apparatus The calibration is done with a standard resistance of 0 1 ohm.

The apparatus is connected to the patient by means of two electrodes The patient should be in moderate expiratory apnea during registration Use of high speed film and simultaneous phonocardiogram or electrocardiogram for timing are indicated

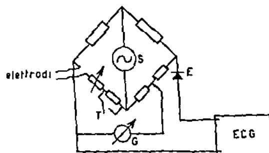


Fig. 4-233. Scheme of rheograph of Holzer and Polzer. *T*, calibration potential; *S*, source of alternating current; *E*, rectifier; *G*, galvanometer.

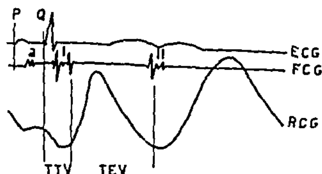


Fig. 4-234. Scheme of the rheocardiogram at the apex with simultaneous ECG and phonocardiogram *TTV*, period of ventricular tension; *TEV*, period of ventricular ejection.

Significance of the Tracing. Polzer and Schuhfried believe that the RG and RCG record *the variations of resistance due to the variations* of the blood flow. The RCG tracings are interpreted as follows (Fig. 4-231) (1) During the period of *ventricular tension*, the tracing reaches its minimum level, (2) during *ventricular ejection*, there is a rapid increase of conductivity, owing to filling of the aorta, and the tracing reaches its peak, (3) at the end of ventricular systole, there is a decrease in conductibility and consequently a drop of the tracing, (4) in *protodiastole*, because of venous *return to the right heart, a rise of the tracing* is observed; (5) in *mid-diastole*, the curve falls because of "accumulation of blood" in the heart chambers A small rise of the tracing marks the presystolic *contraction of the atria*

The tracing is mostly related to the arterial flow during systole and to the venous flow during diastole The 2d sound may coincide with a positive phase (venous inflow predominates—first normal type) or with a negative phase (arterial outflow predominates—second normal type)

The interpretation of Polzer and coworkers was not accepted by other investigators Merlen *and coworkers believe that the RCG shows the* variations in volume, shape, and position of the heart (Holzer et al thought along the same lines in 1948) *Bonjer and coworkers* showed that the variations of impedance, recorded by the peripheral RCG, depend upon variations of volume of the intrathoracic circulation, and that those recorded by the thoracic RCG chiefly express the variations of volume of the heart. Matzdorff (1953a, b) observed in dogs that the closure of the semilunar valves does not modify the tracing and concluded that the heart movements are chiefly responsible for the RCG.

It is well known that the movements of a body in an electric field modify the conductivity by changing the course of the lines of force.

In dogs, Furbetta and coworkers (1956) *described the persistence of the tracing* after interruption of the circulation obtained by clamping the venae cavae, the aorta, and the pulmonary artery, and also during ventricular fibrillation. In addition, they found that the amplitude and shape of the esophageal RCG (Fig. 4-235) resemble the tracings of volume of the various cardiac chambers. This induced *them to consider the RCG as the expression* of the instantaneous volume variation of the organs that are nearer to the exploring electrode.

Several factors can modify the RCG; variations of volume of the heart and vessels, movements of the heart and vessels, ballistic effects of the cardiac activity and surrounding tissues, and variations of blood flow.

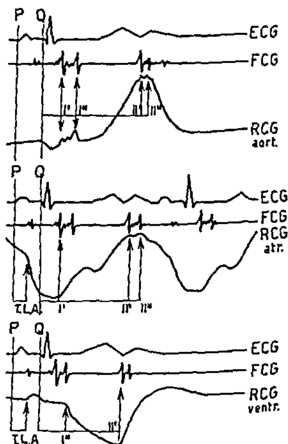


Fig. 4-235. Example of esophageal rheocardiogram with simultaneous ECG and phonocardiogram. Esophageal electrode at the aortic, atrial, and ventricular levels. TLA, period of atrial tension.

Rheocardiogram. The RCG is the graphic representation of the instantaneous variation of electric resistance related to the heart beat and the vascular function. It is obtained when the heart is between the electrodes. Theoretically, it is possible to study the following cardiac phenomena the duration of the different phases of the cardiac cycle, the phases of contraction and dilatation of the heart, and the cardiac output. Not all these theoretical aims are reached, however.

PERIPHERAL RCG According to Holzer and Schulifried, the left leg and the right arm are used as the points of contact in the standard peripheral RCG (Fig 4-236). The interpretation of the records is difficult. Because of the lack of proportionality between amplitude of the RG waves and cardiac output, the peripheral RCG has lost most of its original interest

THORACIC RCG The leads used for the thoracic RCG are the right scapula and the cardiac apex. The precordial electrode may also be placed on the left midaxillary line or over the sternum (Polzer and coworkers, 1956) The normal tracing is characterized by three positive waves The first is *the atrial wave*, which is of moderate amplitude and may be absent or negative It starts in late diastole, coinciding with the 4th sound, and ends during early systole The second wave, called the *arterial wave*, is the result of ventricular ejection. It is of high amplitude, is peaked, and sometimes is diphasic The third wave, a *venous wave*, is small and sometimes notched

Because the pattern of the RCG may change according to different factors, certain technical rules should be followed in order to obtain tracings of a similar configuration the patient should be relaxed and in a state of expiratory apnea, and the electrodes should be accurately placed In the scapula-apex leads, two different types of tracings have been recorded The first is positive in protodiastole, the second is negative One of the tracings may change into the other if the position of the body and the duration of apnea are changed (Matzdorff, 1953).

According to the author and his coworkers, there are intermediate types of tracings in addition to the above The first, called *ventricular* because it resembles a ventricular curve, has a positive atrial wave, a horizontal isometric period, a negative phase during ejection, and a positive phase in protodiastole The second is called *aortic*, because it is similar to the aortic wave, it has a horizontal segment during presystole and the isometric period, a rising

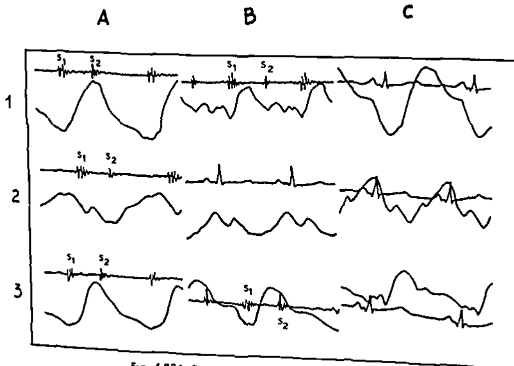


Fig 4-236. Examples of thoracic rheocardiograms.

curve during ejection with a peak at the end of ventricular systole, a small notch in coincidence with the 2d sound, and a final dicrotic wave.

Other tracings, obtained with the esophageal leads, differ in several aspects from the already described curves (Fig. 4-236).

The RCG *tracings obtained in various cardiac conditions* are nonspecific (Matzdorff, 1953a). In *mitral stenosis* (Holzer and Schuhfried), small arterial and high venous waves were found. In *mitral insufficiency*, a rising wave was observed during the isometric period. In *tricuspid insufficiency*, a large positive diastolic wave was described.

INTERPRETATION. Another simultaneous tracing (*ECG or phonocardiogram*) is indispensable for the correct interpretation of the RCG. It is important to evaluate the duration of isometric contraction (interval between the Q of the ECG and the beginning of the RCG arterial wave) and of ventricular ejection time (interval between the beginning and the end of the arterial wave). The average values in normal subjects are 0 045 to 0.100 sec for the former and 0.235 to 0.350 sec for the latter (Matzdorff, 1953). The "atrial interval" is measured by the interval between P of the ECG and the beginning of the RCG atrial wave. It averages 0 050 to 0 075 sec in normal subjects, and 0 100 to 0.120 sec in patients with mitral stenosis.

Calculation of the cardiac output is not possible with the thoracic RCG because the *amplitude of the records has no relationship to the* hemodynamic values

ESOPHAGEAL RCG The esophageal RCG is recorded with two electrodes, the first placed into the esophagus (under fluoroscopic control), and the second anywhere on the body surface (Furbetta and coworkers, 1959). According to the position of the esophageal electrode, it is possible to record aortic, ventricular, and atrial types of tracings

The tracing has great amplitude and shows several details (Fig 4-235). Identification of the various notches of the curve is possible by the comparison with the ECG or phonocardiogram tracings.

The pattern and timing of the tracings obtained at different levels make it possible to record the activity of different sections of the heart and vessels: *aortic* types of tracings are recorded at high levels; *atrial* types at lower levels; *ventricular* types, even lower.

Rheogram. The rheogram is the graphic representation of the instantaneous variation of electric resistance in segments of the body that do not include the heart. Rheograms of the limbs, neck, head, and abdomen have been described. The peripheral RG may be used for *the study of peripheral vascular disturbances*, evaluation of the peripheral blood flow, and calculation of the speed of the pulse waves.

OF THE LIMBS. The tracing resembles the wave of a normal arterial pulsation. The RG can be useful for the study of the peripheral circulation and has the advantage of allowing for an exploration of segments that are not accessible with other methods.

The RG of the limbs is recorded with electrodes placed on different segments of the same limb, either at the same level (*transversal RG*) or at different levels (*longitudinal RG*). It is possible to record the peripheral RG on the fingers and toes.

Clinically adequate tracings require an apparatus of high sensitivity.

The normal RG waves have the same *configuration as the waves of the arterial* pulse (Fig. 4-237). There are a steep and regular positive deflection, a rounded peak, a clear predicrotic wave, and a more or less evident dicrotic wave. In *aortic valvular diseases* and in *arteriovenous fistulas*, the RG shows the typical characteristic of the pulse of such diseases In *tricuspid insufficiency*, a large wave, beginning 0 6010.70 sec after the Q of the ECG, has been *described. According* to Holzer and Schuhfried, such a finding may be interpreted as an expression of the venous engorgement of tricuspid insufficiency A high positive wave in early diastole was found in *right heart failure*, in subjects having high venous pressure but no tricuspid insufficiency *Constriction of the inferior cava* is followed by slight insufficiency of this valve It is possible to make the diagnosis of tricuspid insufficiency by RG if a high systolic wave is also obtained in the rheogram of the neck (Kaindl and coworkers)

The RG permits exact measurement of *the speed of the pulse wave* The time between the foot and the peak of the wave measures the rapidity of the pulse, this rate is modified by lesions of the aortic valve and of the aortic wall

Nyboer (1940) and van der Berg tried to find the relationship between the *RG* wave and blood flow However, because of technical

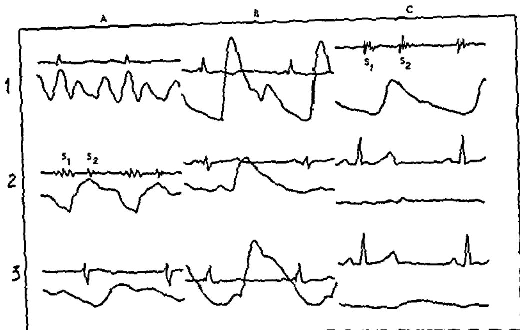


Fig. 4-237. Rheograms: A Of the neck (1, venous type; 2 and 3, arterial type) B Of the limbs in a normal subject (1, upper limb; 2 and 3, lower limbs). C. Of the lower limbs in a patient with arterial occlusion in both limbs (2 and 3)

difficulties it has not been possible to use this as a routine method of investigation. In patients with *decreased blood flow* in a limb, a reduction in the amplitude of the RG waves has been described. In *arterial embolism* or *thrombosis*, no RG waves have been observed in the tracings. The peripheral RG makes it possible to localize the point of *arterial occlusion* in an ischemic limb. Below the site of occlusion, small waves may be recorded as a result of the *development of the collateral circulation*.

The peripheral RG has been used also to study the peripheral transmission of pulse waves during atrial fibrillation, pulsus alternans, etc.

OF THE NECK. Small electrodes, placed laterally on the neck, record arterial, venous, or mixed (carotid or jugular) tracings (Fig. 4-237). Careful localization of two points over the external jugular vein makes it possible to obtain a good venous tracing.

In tricuspid insufficiency, Kaindl and coworkers described a high systolic wave 0.140 sec after the Q wave of the ECG. This wave is synchronous to the similar wave of the jugular pulse and slightly delayed in comparison with the systolic wave of the atrial and superior vena cava pressure tracings.

OF THE HEAD. In order to obtain the RG of the head, two electrodes are placed on the forehead, and either on the occiput or behind the mastoid. The tracings result from the summation of all the intra- and extravascular phenomena of the head.

The normal RG of the head is characterized by an initial rapid upstroke, a plateau-like peak, and a final drop of the curve. In *arteriosclerotic* subjects, the curve rises slowly and may be interrupted by a notch, with delay of the peak.

ABDOMINAL RG. The most interesting abdominal rheogram is the hepatic, obtained by placing two electrodes on the hepatic area. The tracing shows arterial, venous, and sometimes atrial waves.

In severe hepatic diseases, such as *liver cirrhosis*, modifications of the tracing have been observed. In *heart failure*, three different changes were described: a high presystolic wave, a high postsystolic wave, or three positive waves of the same shape and height. In *tricuspid insufficiency*, Heeger and Polzer found a high positive diastolic wave, somewhat similar to those observed on the limbs. This wave decreased after the inferior vena cava had been clamped.

Tracings of the *abdominal vessels* (the aorta and its branches) have been recorded with an electrode placed anteriorly on the umbilicus and one posteriorly. With this method, it has been possible to localize the site of an arterial occlusion.

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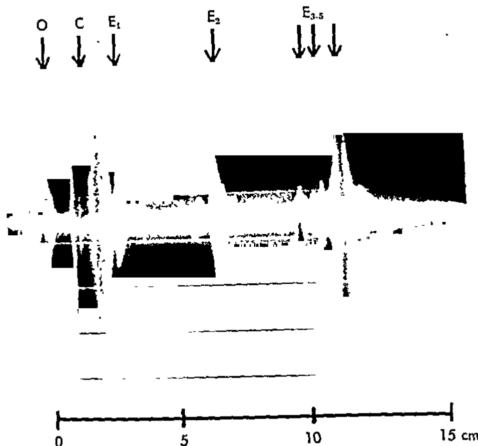


Fig. 4-238. Echogram obtained on the screen of a cathode ray tube when the quartz crystal was placed over the precordium of a patient with normal heart size On the scale, 1 cm represents the time necessary for the impulse to traverse 1 cm to and fro in blood The same scale was used for the musculature, in which the velocity of sound differs only slightly from that in blood O, starting signal, which indicates the time the sound impulses leave the quartz crystal, C, multiple echo signals from the anterior wall of the thorax just beneath the quartz crystal. The vertical oscillations E_1 to E_5 fluctuate along the horizontal axis synchronously with the heart beat, and thus emanate from surfaces whose distance from the crystal on the precordium varies with the cardiac cycle E_2 shows the largest and most rapid fluctuations along the horizontal axis (about 2 cm).

ULTRASONIC CARDIOGRAM IN MAN

If ultrasonic impulses are emitted at a frequency of 2 5 Mc from a crystal placed against the chest, strong echoes will be recorded from the chest wall and the anterior parts of the underlying lung tissue Owing to the high absorption by the aerated lung tissue, the impulses will not be propagated more than 5 to 10 cm into the lung tissue, in other words, echograms will be obtained only from the superficial tissues In the precordium where . . . al subjects, these echoes are reflected from layers situated 3 to 12 cm from the skin of the chest (Fig 4-238) The vertical oscillations fluctuate along the horizontal axis representing boundaries moving to and from the anterior surface of the chest. These movements are synchronous with the heart beat They can be continuously recorded together with an electrocardiogram, a phonocardiogram, or an intracardiac pressure curve This tracing of the movements of the heart is called an *ultrasonic cardiogram* (UCG).

Figure 4-240 shows normal UCGs recorded with the crystal placed over different points

17

Cardiac studies by ultrasounds

INGE EDLER

Ultrasonic cardiography is a method for studying the motions of the heart by means of sound impulses emitted and received by a quartz crystal placed against the chest.

Method. Sound vibrations of a frequency far above the threshold of the human ear are generated in a crystal of quartz or barium titanate The vibrations produced can be emitted in the form of a beam in any desired direction During their passage through a medium, their intensity is diminished by absorption In air, the absorption is considerable, in fluids and in biologic tissue, it is much less If sound impulses passing through a given medium impinge upon another medium of different density, part of them will be reflected, the angle of reflection being equal to the angle of incidence. If the path of propagation of the impulses is perpendicular to the surface of such a layer, i e, the reflecting surface, the impulses will be reflected as an echo to its site of origin, i e, to the crystal. By emitting ultrasonic vibrations and receiving their "echoes," it is possible to measure the distance between the origin and the reflecting surface, provided, of course, that the speed of propagation of the impulses in the medium between the crystal and the reflecting surface is known All impulses emitted are registered as vertical oscillations on the left part of the screen of a cathode ray tube (Fig 4-238) As soon as the echo returns to the crystal, which now acts as a microphone, an oscillation will appear on the screen somewhat to the right of the first vibration The horizontal distance between these two points is a measure of the time necessary for the impulses to travel from the crystal to a reflecting surface and back again If the velocity of the sound is the same in all the media it traverses, the horizontal distance between the vertical oscillations on the screen will be a measure of the distance between the crystal and the reflecting surfaces

In *ultrasonic cardiography,* ultrasound with a frequency of 2.5 million cycles per second (2 5 Mc) is generally used. The duration of the impulse is 2 5 by 10^{-6} sec. As soon as the impulse has been generated and has left the crystal, the latter is automatically switched over for reception of the echo. Impulses are emitted from the crystal at the rate of 200 per sec, which means that the distance between the origin to the reflecting surface is measured 200 times per second The oscillations marking the moment in which the sound impulses leave the crystal always appear at the very same position on the screen

ECHOES FROM VARIOUS PARTS OF THE CARDIOVASCULAR SYSTEM

In experiments on the isolated heart, Edler and Hertz (1954) have shown that *ultrasounds directed to the blood-filled heart are reflected from the surface between the heart wall and the blood* The interventricular septum, the atrioventricular wall, and the walls of the vessels reflect sound waves. When a thrombus was placed in a cardiac chamber, multiple echoes were recorded from the site occupied by the thrombus Figure 4-239 shows an echogram of a blood vessel placed in water. The echogram is exactly the same when blood is substituted for the water (Edler et al, 1954, 1955, Hertz and Edler)

Wild et al. demonstrated the position of an infarction in the isolated human heart by means of ultrasonics. They also located the left coronary artery and the aorta by this method.

Edler et al (1959) showed that the heart valves also reflected ultrasounds.

along the path will be reflected by these surfaces back to the crystal The distance between the skin of the chest and the mitral valve corresponds to that between O and E_2 (O = outgoing impulse, see Fig. 4-238). If the needle is inserted in the 3d intercostal space of the cadaver and directed 10 to 15° medially, it will pass through the interventricular septum and the outflow tract of the left ventricle just below the aortic valve and through the atrioventricular (AV) wall into the left atrium.

RECORDING OF VALVULAR MOVEMENTS

In a series of experiments on the isolated heart of the calf, the aortic and mitral valves were alternately opened and closed by intermittent perfusion (Edler et al, 1960). The movements were photographed with a cinecamera placed over the ostium on the atrial, respectively the aortic side. The ultrasonic crystal was placed against the anterior surface of the right ventricle in a position correspond-

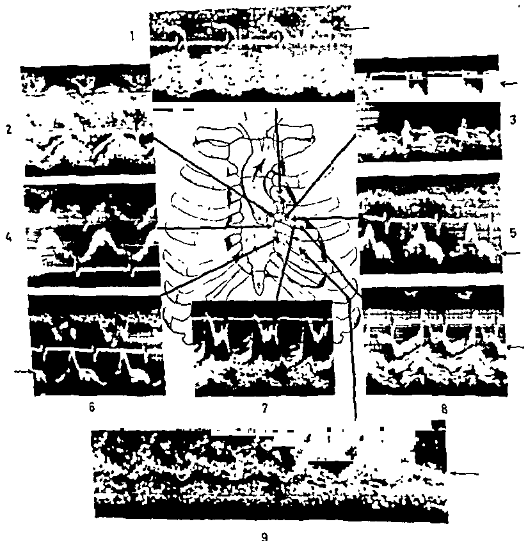


Fig 4-240 *Variation in pattern of curve with position of crystal* Arrow heads denote site of application of crystal in the precordium 1, the pulmonary artery (see Fig 4-243) Arrow heads in 5 and 8 denote the curves of the echo signals, with the wide and rapid movements recorded from the 3d left intercostal space The same type of curve is seen in 7. In 3, this curve is only fragmentary Arrow head in 9 denotes the curve from the posterior heart wall

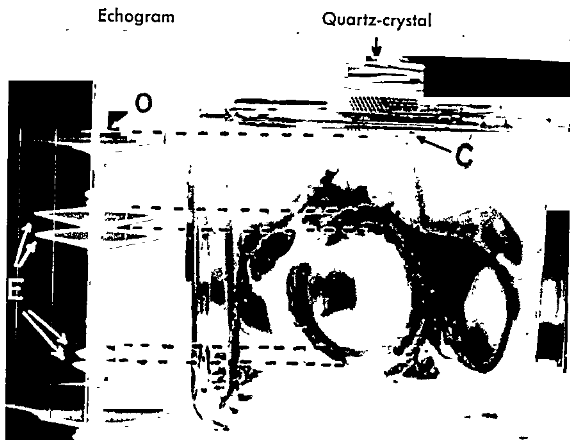


Fig. 4-239. Echogram of the pulmonary artery in the calf. The crystal was placed over the preparation, which was suspended in water. C, surface between the quartz crystal and the water (photograph of horizontal screen of cathode ray tube with echogram is placed vertically to facilitate comparison with anatomy of vessel), O, starting signal, i e, moment of departure of impulses from crystal; E, echo signals from the outer and inner surfaces of the walls of the pulmonary artery.

of the precordium. Certain conditions, such as *obesity* or *severe emphysema*, impair the quality of the UCG In all tracings, the amplitude of the movement of the posterior wall is fairly small. The movements are more rapid during systole than during diastole (Fig 4-240, 9) From a limited area 1 to 4 cm from the sternal margin in the left 3d intercostal space, over the left fourth rib, and often also in the 4th left intercostal space, one of the vertical oscillations fluctuates considerably (about 2 cm) and very rapidly along the horizontal axis (Fig 4-240, 5, 7, 8).

In advanced *dilatation of the left ventricle*, the crystal must be placed somewhat lower (4th left intercostal space) and more laterally in order to record these characteristic echoes. In *cardiac dilatation*, the posterior wall is further from the crystal and then, of course, the wave that is reflected from that wall will be more distant from the initial deflection of the UCG.

In order to ascertain which structures were perpendicular to the direction of the waves and thereby responsible for the echoes, experiments were performed on cadavers. From the area in the left 3d intercostal space, where the rapid wide movements are recorded in normal subjects, a needle was inserted along the path of the beam After traversing the wall of the chest, the needle was found to pass through the upper part of the right ventricle, the interventricular septum, the outflow tract of the left ventricle, and the anteromedial leaflet of the mitral valve, to the left atrium, and then, through the posterior wall of the left atrium or the posterolateral leaflet of the mitral valve, into the left ventricle. Figure 4-241 shows the passage of the needle through the anteromedial leaflet of the mitral valve in a cadaver pierced in this way. The anterior wall of the right ventricle, the anterior mitral valve, and the posterior wall of the heart are pierced perpendicularly by the needle, so that impulses propagated

1 to 4 cm lateral to the margin of the *sternum* correspond to the movements of the *anteromedial leaflet of the mitral valve*. The same type of tracing is obtained when the crystal is placed over the fourth rib, and sometimes when it is placed in the 4th intercostal space (Figs. 4-240, 5, 8; 4-244). This characteristic curve is, as a rule, readily obtainable. However, in severe *emphysema* and *obesity*, it is sometimes difficult to trace satisfactory curves.

If the beam is directed more laterally, oscillations from the posterolateral leaflet of the mitral valve will also be recorded (Fig 4-245b). These curves give a picture of the movements of the mitral funnel.

Selective recording of the movements of the anteromedial leaflet, however, provides a measure of the functional state of the mitral orifice Figures 4-244 and 4-246 show a normal tracing from the anteromedial leaflet For each cardiac cycle, the curve shows two waves, E and A, separated by a plateau or a gently falling segment. The A wave corresponds to the *atrial contraction* and coincides with the 4th heart sound of the phonocardiogram (Fig 4-246).

In *atrial flutter*, the UCG shows multiple A waves during ventricular diastole Each wave occurs about 0 10 sec after a P wave of the ECG In *atrial fibrillation*, the A wave is missing because the atrial wall has only fibrillary vibrations.

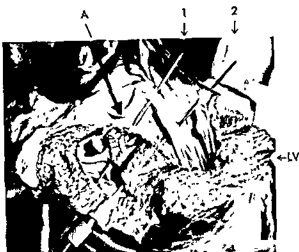


Fig. 4-242. Calf's heart opened after conclusion of experiment with intermittent perfusion to produce opening and closing movements of the aortic and mitral valves (see text). Needles 1 and 2 are inserted in two well-defined positions in which the crystal must be placed for recording the characteristic movements of the aortic and mitral valves A, right posterior leaflet of aortic valve, *LV*, lateral wall of left ventricle In the left lower corner, the needles pass into the right ventricle and then through the interventricular septum and the outflow tract of the left ventricle Needle 1 passes immediately below the posterior left aortic leaflet and through the AV septum into the left atrium Needle 2 passes further through the anteromedial leaflet of the mitral valve to the left atrium

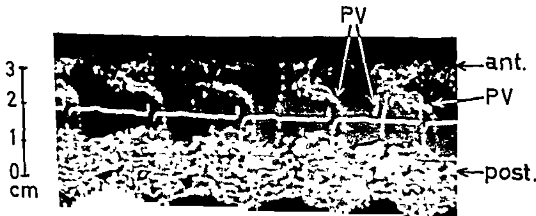


Fig 4-243 Ultrasonic cardiogram (UCG) of pulmonary artery and pulmonary valve recorded from a point in the 2d left intercostal space The upper part of the picture corresponds to the region nearest the crystal ant, ventral part of pulmonary artery, *post*, dorsal wall of pulmonary artery, *PV*, echo signal from one of the pulmonary valves. During ventricular diastole, the valve moves only slightly, at the beginning of ventricular systole, the valve moves rapidly away from the crystal

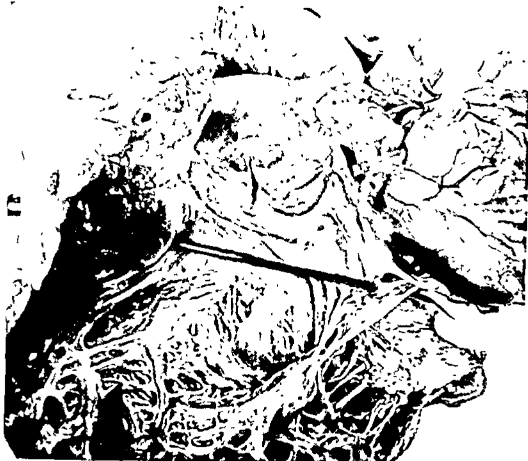


Fig. 4-241. Isolated human heart, punctured through chest wall in situ. The path of the needle corresponds to the path of the sound beam when the wide and rapid echo fluctuations are recorded from the 3d intercostal space (E_2 in Fig 4-238 and parts 5, 7, and 8 in Fig. 4-240). The visible part of the needle passes from the interventricular septum to the left of the picture and proceeds under the aortic valves and through the anteromedial leaflet of the mitral valve into the left atrium. Two aortic leaflets are visible above the needle.

ing to the point which was found to be situated under the 3d left intercostal space 3 to 4 cm from the midline of the sternum Only when the beam was placed in two definite directions did vertical oscillations fluctuate rapidly along the horizontal axis. The angle between the two paths was 10 to 15° The patterns of the two recorded tracings differed widely from one another. Comparison between these curves and simultaneous pressure tracings of the left ventricle, and pictures from the film showing the movements of the mitral and aortic valves, revealed that *the ultrasonic tracings reflected movements of the mitral valve and aortic valve, respectively.* Needles inserted in these two directions pierced the anteromedial leaflet of the mitral valve perpendicularly, and passed just below the left posterior aortic leaflet (Fig. 4-242). When these valves were fixed during the experiment, the amplitude of the fluctuations decreased to almost nil.

CLINICAL USE OF ULTRASONIC CARDIOGRAPHY

From the Pulmonary Artery and the Aorta. Medially in the 2d left intercostal space, oscillations are usually readily obtained from the ventral wall as well as from the dorsal wall of the *pulmonary artery* (Figs. 4-240, 1; 4-243), and similar signals can be recorded from the *aortic arch* if the crystal is placed over the suprasternal notch. The rapidly fluctuating echoes from the lumen of the pulmonary artery at the beginning of systole reflect the opening of the pulmonary valve (probably its posterior leaflet). This movement is demonstrated most easily in patients with dilatation of the pulmonary artery. The crystal should be directed somewhat caudally.

From the Mitral Valve. As mentioned above, the rapidly fluctuating deflections registered with the crystal in the left 3d intercostal space

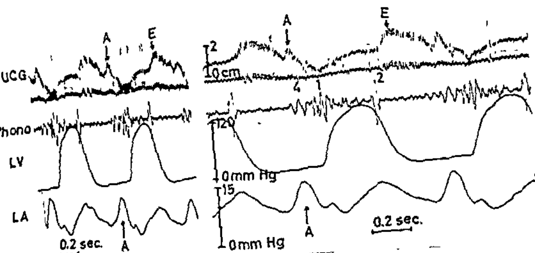


Fig. 4-246. Ultrasonic cardiogram of anteromedial mitral leaflet recorded by a direct-writing electrocardiograph simultaneously with a phonocardiogram, and left atrial LA and left ventricular LV pressures. For explanation of the waves A and E in the UCG, see text. In the phonocardiogram tracing, 1, 2, and 4 are the 1st, 2d, and 4th heart sounds

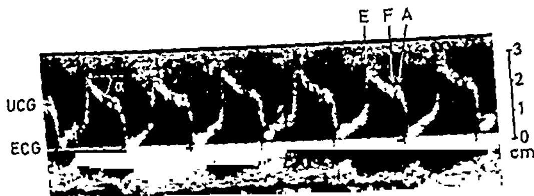


Fig. 4-247 Ultrasonic cardiogram from the anteromedial mitral leaflet in mitral stenosis. The normally steep drop E to F is replaced by a slowly declining line throughout or during a major part of diastole The angle α is a measure of the range of movement of the anteromedial mitral leaflet after the maximal opening of the mitral ostium early in ventricular diastole

In the early stage of *ventricular systole*, the curve falls abruptly (B to C in Fig. 4-244) and then gently rises during the rest of ventricular systole (C to D). The distance between the reflecting surface and the crystal on the chest is greatest at C When the P-Q time is normal, the declining limb of the A wave continues in the same direction (B to C) while the two components are separated by a horizontal segment in AV *block* B to C to D coincides with *ventricular systole* Immediately after the 2d aortic sound, the UCG rises steeply to the E wave (Fig 4 246) D to E corresponds to the shift of the anteromedial mitral leaflet into the lumen of the left ventricle during *ventricular relaxation* The distance *O* to E (*O* = outgoing impulse, see Fig 4-238) corresponds to the shortest distance between the crystal and the mitral valve during the cardiac cycle, i e , when the mitral ostium is widely open. After E, the curve declines at an increasing rate to the point F, after which it runs horizontally or rises slowly until the next A wave occurs. The distance E to F corresponds to the successive return of the valve from maximal opening toward closure The A wave represents increased open-

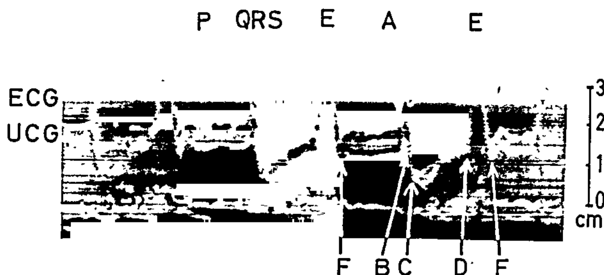


Fig. 4-244. Normal UCG curve of anteromedial leaflet of mitral valve. Simultaneous ECG. Upper part of picture faces starting signal (O, not shown in picture), which represents the position of the quartz crystal in the left 3d intercostal space. The angle α is 65 to 75° in normal subjects

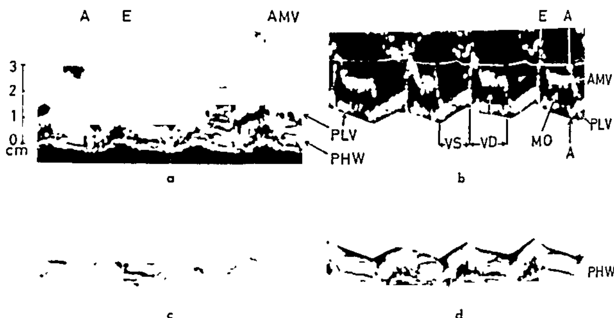


Fig. 4-245. Ultrasonic cardiogram of mitral funnel and posterior wall of left ventricle. a. When recording the movements of the anteromedial mitral valve, a complicated curve (multiple echoes) can be obtained by a slight laterocaudal change in the direction of the beam. *AMV*, anteromedial mitral leaflet; *PLV*, posterolateral mitral leaflet; *PHW*, posterior wall of left ventricle c. Normal tracing of posterior wall of left ventricle. b. and d Section of a, divided horizontally and separated. The lower part d shows the same type of curve as does c, of the posterior wall of the left ventricle. The upper part (b) shows two echoes, *AMV* and *PLV*, which diverge markedly from one another at the beginning of diastole *VD*, and then run parallel until the occurrence of atrial systole *A*, when they again separate, though less markedly. During ventricular systole *VS*, these two echo signals coincide. The distance between *AMV* and *PLV* during ventricular diastole is a measure of the size of the mitral funnel in the section passed by the impulses. *MO*, mitral ostium.

The possibility of recording movements of the anteromedial and posterolateral mitral leaflets, as well as of the posterior wall of the left ventricle just behind the funnel, is apparent from Fig. 4-242.

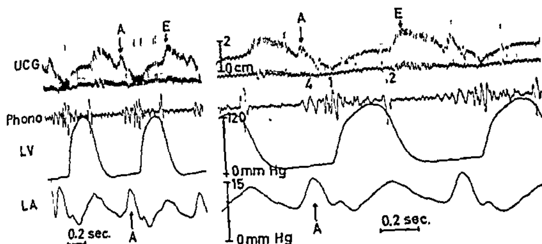


Fig 4-246. Ultrasonic cardiogram of anteromedial mitral leaflet recorded by a direct-writing electrocardiograph simultaneously with a phonocardiogram, and left atrial *LA* and left ventricular *LV* pressures For explanation of the waves A and E in the UCG, see text. In the phonocardiogram tracing, 1, 2, and 4 are the 1st, 2d, and 4th heart sounds.

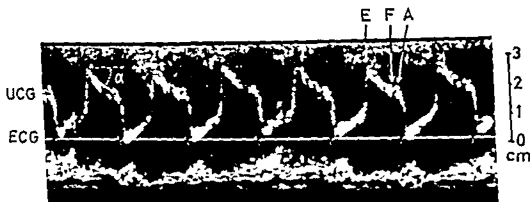


Fig. 4-247. Ultrasonic cardiogram from the anteromedial mitral leaflet in mitral stenosis. The normally steep drop E to F is replaced by a slowly declining line throughout or during a major part of diastole. The angle α is a measure of the range of movement of the anteromedial mitral leaflet after the maximal opening of the mitral ostium early in ventricular diastole

In the early stage of *ventricular systole*, the curve falls abruptly (B to C in Fig 4-244) and then gently rises during the rest of ventricular systole (C to D). The distance between the reflecting surface and the crystal on the chest is greatest at C When the P-Q time is normal, the declining limb of the A wave continues in the same direction (B to C) while the two components are separated by a horizontal segment in AV *block* B to C to D coincides with *ventricular systole*. Immediately after the 2d aortic sound, the UCG rises steeply to the E wave (Fig. 4-246). D to E corresponds to the shift of the anteromedial mitral leaflet into the lumen of the left ventricle during *ventricular relaxation*. The distance O to E (O = outgoing impulse, see Fig 4-238) corresponds to the shortest distance between the crystal and the mitral valve during the cardiac cycle, i e., when the mitral ostium is widely open. After E, the curve declines at an increasing rate to the point F, after which it runs horizontally or rises slowly until the next A wave occurs. The distance E to F corresponds to the successive return of the valve from maximal opening toward closure The A wave represents increased open-

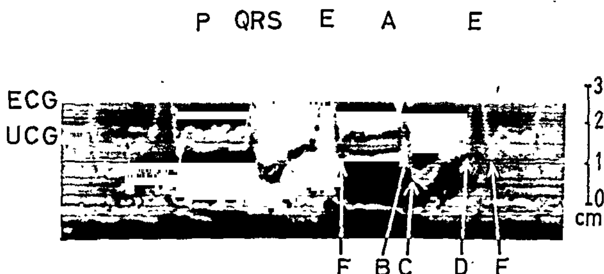


Fig. 4-244. Normal UCG curve of anteromedial leaflet of mitral valve. Simultaneous ECG. Upper part of picture faces starting signal (O, not shown in picture), which represents the position of the quartz crystal in the left 3d intercostal space The angle α is 65 to 75° in normal subjects.

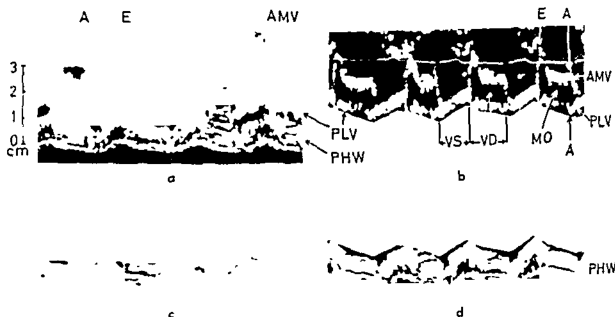
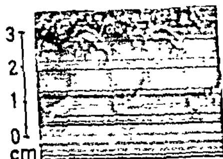


Fig. 4-245. Ultrasonic cardiogram of mitral funnel and posterior wall of left ventricle. a. When recording the movements of the anteromedial mitral valve, a complicated curve (multiple echoes) can be obtained by a slight laterocaudal change in the direction of the beam *AMV*, anteromedial mitral leaflet; *PLV*, posterolateral mitral leaflet, *PHW*, posterior wall of left ventricle. c. Normal tracing of posterior wall of left ventricle. b. and d Section of a, divided horizontally and separated The lower part d shows the same type of curve as does c, of the posterior wall of the left ventricle The upper part (b) shows two echoes, *AMV* and *PLV*, which diverge markedly from one another at the beginning of diastole *VD*, and then run parallel until the occurrence of atrial systole *A*, when they again separate, though less markedly. During ventricular systole *VS*, these two echo signals coincide. The distance between *AMV* and *PLV* during ventricular diastole is a measure of the size of the mitral funnel in the section passed by the impulses. *MO*, mitral ostium

The possibility of recording movements of the anteromedial and posterolateral mitral leaflets, as well as of the posterior wall of the left ventricle just behind the funnel, is apparent from Fig. 4-242.







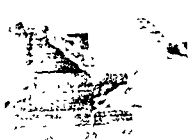


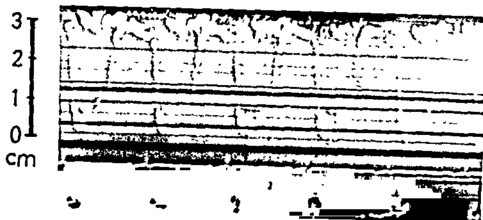
Fig. 4-249. Ultrasonic cardiogram from anteromedial mitral leaflet in a patient with mitral stenosis who had twice undergone commissurotomy. The pulmonary wedge pressure was 20 mm Hg before the first operation and 11 mm Hg after operation. Three years later it was 21 mm Hg. At the first operation the mitral ostium was widened to about 1½ fingers. At reoperation 3 years later, the ostium was very narrow and was widened to permit the passage of 2½ to 3 fingers. *Below left:* the angle α is smaller than after the first operation (restenosis). After reoperation, a bigger angle exists again

25° If the angle is less than 25°, it may be assumed that regurgitation, if any, is not serious In moderate and severe mitral stenosis, the A wave, which normally occurs in presystole, is, as a rule, missing, despite the presence of sinus rhythm This is because the increase of pressure during atrial contraction does not allow further opening of the mitral valve In mild stenosis, as well as in stenosis combined with significant insufficiency, the angle is usually between 30 and 50° In *isolated mitral insufficiency*, it is 65 to 75°, as in normal subjects

The UCG has been successfully used for the selection of patients for mitral commissurotomy and for the evaluation of the effect of the operation (Edler et al, 1954, 1955, 1957, Hertz and Edler) Figure 4-248 shows the UCG before and after commissurotomy The A wave is visible after operation, when the atrial pressure has become nearly normal Restenosis is demonstrable in the UCG before the appearance of any symptoms. Figure 4-249 shows the UCG taken at various intervals in a patient who had undergone commissurotomy twice

From the Outflow Tract of the Left Ventricle and the Movements of the Aortic Valve. If the direction of the beam is changed 5 to 10° medially during registration of the movements of the anteromedial leaflet, it will alter the pattern of the tracing (Figs 4-240 and 4-250). Examinations of cadavers revealed that this modified type of tracing represented the AV wall between the mitral valve and the aortic valve As a rule, an echo was obtained at the same time from that part of the surface of the ventricular septum which lines the outflow tract of the left ventricle.

In *aortic stenosis*, the amplitude of the move-



PREOPERATIVE UCG.





POSTOPERATIVE UCG

UCG 3 YEARS AFTER OP.

Fig. 4-248. Ultrasonic cardiogram from the anteromedial mitral leaflet in mitral stenosis before and after commissurotomy. *Above* before operation; *below left:* some weeks after operation; *below right:* 3 years after operation Before operation, the patient coughed even on slight exertion, suggesting congestion of the pulmonary circulation. The pulmonary wedge pressure was 35 mm Hg. At operation, the narrow mitral ostium (only fingertip size) was widened to permit the passage of two fingers. After operation, the pulmonary wedge pressure was 14 mm Hg Four years after operation, the patient was still free of symptoms

ing of the ostium during presystole Figure 4-246 shows the movement of the anteromedial leaflet registered simultaneously with the phonocardiogram and the pressures of the left atrium and ventricle.

In *aortic valvular disease* without involvement of the mitral valve, and in different types of *congenital heart disease,* the UCG from the anteromedial mitral leaflet is normal.

In *mitral stenosis,* the pattern of the tracing is quite different (Fig. 4-247) The normally steep drop E to F is replaced by a slowly declining line throughout or during the major part of diastole. This means that, after maximal opening of the valve at the beginning of ventricular diastole, the tracing moves only a relatively short distance away from the crystal *This pattern is characteristic of mitral stenosis.*

In normal subjects, in aortic valvular disease, and in various types of congenital heart disease, the angle α that the E to F segment of the curve subtends with the horizontal plane is 60 to 75° (Fig 4-244) The curves are registered under the following standard conditions. (1) film rate, 40 mm/sec, (2) 10 mm in the vertical plane on the film corresponds to 10 mm movement of the reflecting surface of the heart. In mitral stenosis, this angle α is always less than 50° (author's personal experience with 400 cases of mitral stenosis). The angle α varies with the degree of stenosis In advanced cases, it is less than 10 to 12°. If the opening of the mitral ostium corresponds to the width of the index finger, the angle is about

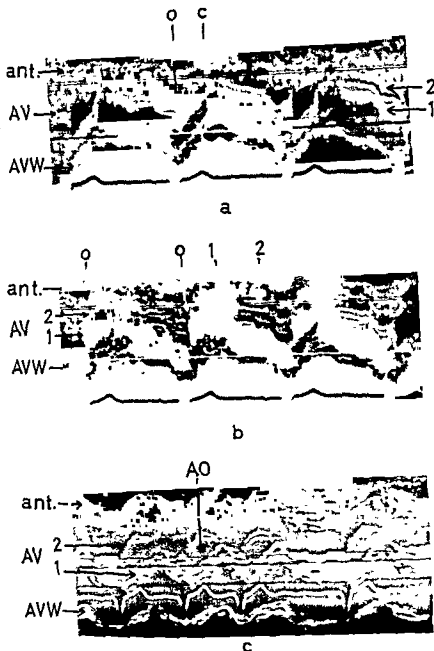


Fig 4-251 Ultrasonic cardiogram showing movements of aortic valve with the impulses directed from the 3d intercostal space toward the aortic ostium *AVW* and *ant*, atrioventricular wall and left interventricular septal wall, respectively, *AV*, movements of aortic valve (1, left posterior leaflet; 2, anterior aortic leaflet), O, rapid opening of aortic valve at beginning of systole; C, rapid movement of aortic valve on change from systole to diastole

a and b are from a normal subject The tracings were taken with slightly different angles of the impulses and are somewhat fragmentary During early ventricular systole, curves 1 and 2 separate During ventricular diastole, curves 1 and 2 are close to one another and parallel c Movements of aortic valve in aortic stenosis Smaller amplitude than in a and b The distance between 1 and 2 during ventricular systole indicates opening of aortic ostium *AO*.

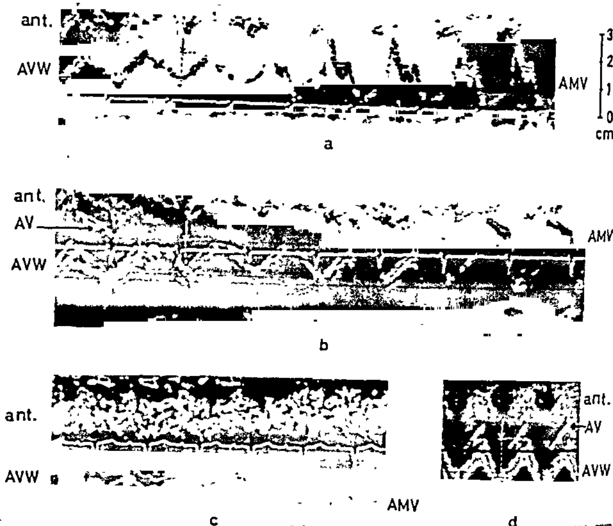


Fig. 4-250. Ultrasonic cardiogram from the left ventricular outflow tract and the anteromedial mitral leaflet The crystal was placed in the 3d intercostal space 1 to 3 cm from the left sternal border. If the direction of the beam forms an angle of 5 to 10° with the vertical plane, a curve will be obtained for the atrioventricular wall (AVW). If this angle is diminished, a tracing for the anteromedial mitral leaflet (AMV) will be obtained instead.

ant = surface of left interventricular septal wall which is closer to the crystal than the atrioventricular wall *ant* and *AVW* thus represent the anterior and posterior borders of the left ventricular outflow tract

a. Normal. b. Mitral stenosis *AMV* shows typical curve seen in mitral stenosis c. Aortic stenosis. d. Aortic insufficiency

Amplitude of movement of *AVW* during ventricular systole (dashed line at arrow head) is in normal subjects (a) and in pure mitral stenosis (b) about 0.8 to 1 0 cm. In aortic valvular stenosis (c), the amplitude of *AVW* is reduced to 1 to 2 mm during ventricular systole. In aortic valvular insufficiency (d), the amplitude is increased, about 1 5 cm.

AV in (b) and (d) is echo from aortic valve

ments of these walls during ventricular systole is much smaller than normally. If the rays are directed still more medially, there will be an additional rapidly fluctuating echo between the anterior and posterior walls of the outflow tract (Fig. 4-251). The amplitude of these rapid fluctuations is greatest at the beginning of systole and at the moment of the 2d aortic sound *This echo represents the movement of the aortic valve* The pattern of the tracing resembles that from the left posterior aortic leaflet in the experimental investigations on the isolated heart In some cases, echoes were also recorded from two valves, the echoes diverging at the beginning of ventricular systole and converging at the end (Fig. 4-251b). Movements of smaller amplitude and slower movements have been recorded in *aortic stenosis*

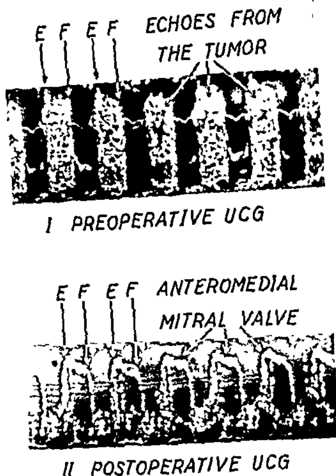


Fig. 4-254. Atrial myxoma I Ultrasonic cardiogram of anteromedial mitral leaflet completely masked by multiple echo signals from the inner aspect of the left atrium, which operation revealed to be an atrial myxoma adherent to mitral leaflet II. Ultrasonic cardiogram after subtotal removal of tumor. The E to F segment of the curve is the same type as that seen in mitral stenosis (see Fig 4-247)

(Fig 4-251c). However, refinement of the method is necessary if it is to be useful as a tool in the diagnosis and evaluation of the severity of aortic stenosis.

From the Tricuspid Valve. If the crystal is directed from the medial part of the left 3d intercostal space toward the tricuspid valve, a very rapidly fluctuating echo will be reflected from a surface situated somewhat deeper than the interior surface of the right ventricle *These echoes represent the movements of the tricuspid valve* (Fig 4-252) Sometimes the same film will show echoes from the tricuspid and mitral valves, the latter reflexes come from a deeper and more lateral surface (Fig 4-240, 6)

Figure 4-253 shows a cardiogram from a patient with severe enlargement of the right atrium. The tricuspid valve was located by the UCG vertically under a point in the left 4th intercostal space, 8 cm from the midline of the sternum This position of the valve was confirmed by subsequent catheterization of the heart

In Atrial Septal Defect. In atrial septal defect, the anteromedial mitral leaflet and the left surface of the interventricular septum are situated much deeper than normal This is because of widening of the outflow tract of the right ventricle whenever the shunt is moderate or marked. The movements of the tricuspid valve are easy to register in such cases

In Atrial Thrombosis and Myxoma. Multiple echoes between the anteromedial mitral leaflet

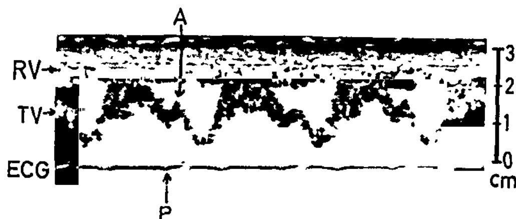


Fig. 4-252. Ultrasonic cardiogram from tricuspid valve *TV*. *RV*, anterior wall of right ventricle; *A*, wave during atrial systole. Crystal placed over left 3d intercostal space.

VD VS
1
TO
2
3
P

VS VD VS
E A
TO
3
2
1
0
cm
1
2
ECG
3
P P P

Fig. 4-253. Ultrasonic cardiogram from two of the tricuspid leaflets. 1, echo from the valve nearest the crystal; 2, echo from one of the other tricuspid leaflets, 3, echo from the interventricular septum; *TO*, tricuspid ostium, *VD*, ventricular diastole; *VS*, ventricular systole. Tricuspid ostium widest at beginning of diastole (*E*) and during atrial systole (*A*). *P*, P wave of ECG. Diagnosis: *tricuspid stenosis*.

18

Studies of cardiac function by the ultrasonic Doppler method

TSUNEO YOSHIDA

Because of its physical properties, resulting from its high frequency, ultrasound has good transmission and sharp direction of propagation in a given substance, and can therefore be used for studying the structure and function of organs

One of the diagnostic applications of ultrasound to the study of the heart is the *pulse method*, which has been developed by Edler and Hertz, Effert, Wollheim, and others[1] This method is based on the different acoustic impedances of ultrasounds when encountering two different kinds of tissue in the human body This method is employed to measure the size of the heart, the thickness of the heart wall, the presence of pericardial fluid, etc Moreover, a kinetographic study of the heart wall (ultrasonic cardiogram, UCG) can be made by means of a continuous recording, on the screen of an oscilloscope, of the echo motion that occurs during the heart beat

Another diagnostic application of ultrasound to the heart is based on the Doppler method This method utilizes the *Doppler effect*, which occurs when an ultrasound is reflected from a target in motion The ultrasonic Doppler method supplies information about the target's motion, i e, about the motions of various parts of the heart.

PRINCIPLES OF THE METHOD

Precise Direction of Propagation of Ultrasound. When a sound is transmitted from a disk source, its energy is distributed symmetrically around the normal at the center of the disk, and the main lobe of the distribution surface of energy is determined by the following solid angle θ.

$$\sin\theta = 1.22\lambda/d$$

where λ = wavelength of the sound
d = diameter of the disk

Regarding ultrasound, θ is small, since λ is short, i e, the beam of ultrasound has a slight divergence while showing a precise direction of propagation

In order to obtain information about objects that reflect this sound, it is necessary to send it in a given direction with little divergency and to detect the reflected wave only from a definite direction The above properties of ultrasound meet this demand This is one of the reasons why ultrasound is used for scanning not only the inner aspects of the human body but also various other objects Audible sounds cannot be used for such purposes because of their long wavelength, which causes a wide divergence of their beams

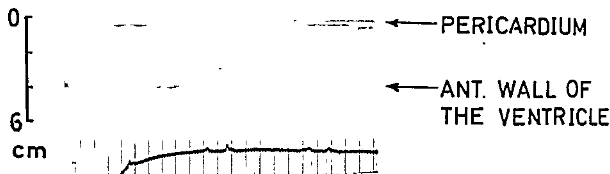
Ultrasonic Doppler Method. When a continuous beam of ultrasounds is reflected from a moving target, it undergoes a *Doppler effect, because of the motion of the target, this causes a slight change in the frequency of the sound*

The following relationship is assumed to exist between the frequency of the initial wave f and that of the reflected wave f'

$$f' = f\frac{c}{c - 2\mu\cos\alpha} \qquad (2)$$

where μ = velocity of the target
c = velocity of the ultrasound
α = angle between their directions

[1] See Part 4, Chap. 17 *Editor*



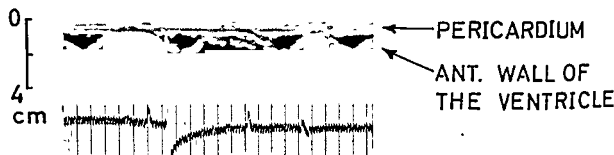


Fig. 4-255. Pericarditis with effusion I Distance between pericardium and anterior wall of ventricle as seen in UCG is due to accumulation of fluid II Distance reduced after aspiration.

and the posterior wall of the left atrium appear in atrial thrombosis and in atrial myxoma (Edler, 1955, Edler et al, 1960a) Multiple echoes in a patient with sinus rhythm suggest a tumor of the left atrium Figure 4-254 shows a tracing from the first myxoma diagnosed by this method Effert has described a similar case in which the UCG showed exactly the same pattern In thrombosis, the curve usually appears to be more stratified.

In Pericardial Effusion. In pericardial effusion the echo from the anterior wall of the right ventricle is separated from that of the anterior chest wall and the pericardium (Fig 4-255), normally these echoes fuse together.

CONCLUSION

Ultrasonic cardiograms can be used clinically, mainly for evaluating the degree of mitral stenosis, in the diagnosis of pericarditis, and in general for determining the amount of fluid in the pericardium The method is rapid, it will show whether commissurotomy is indicated or not, and it does not require more time than a routine electrocardiographic examination Ultrasonic cardiograms also make it possible to study the movements of the valves in relation to the heart sounds With further refinement of the method, it should be possible to study the hemodynamics of the heart in great detail.

quency that is in proportion to the velocity of the target as expressed by Eq. (3).

Equipment and Method. The apparatus contains a *high-frequency oscillator*, an electrosonic transducer, a detector, an audio frequency amplifier, filters, monitors, and a recorder (Fig. 4-256A).

The *high-frequency oscillator* has a self-induced oscillation of 1 to 3 watts and an operating *frequency of 3 megacycles* (Satomura, 1957) *This results in a Doppler beat* frequency *of 100 to* 1,000 cycles, because of the motion of the heart, and is suitable for seeking the target while an audiophone is employed as a monitor

The high-frequency energy is conducted to an *electrosonic transducer* of barium titanate The positive pole *of the transducer is a* disk, 1 cm in diameter, which is divided into an inner and an outer part by a concentric circle The inner and outer rings are used, respectively, for sending and receiving The calculated value of the ultrasound power is less than 20 to 50 *mw/cm*^{3} The θ defined in Eq (1) *is about 4°. Cavitation, the most important* cause of physiologic effects of ultrasound on living tissue, develops mainly at over 300 mw/cm^2 Therefore, the above intensity of ultrasound can be used for a few minutes without physical hazards to the subject. The *ring acting* as a receiver picks up *not only the* reflected wave but *also the initial* wave, which is propagated electrically, mechanically, or both ways, from the adjacent ring Thus causes a beat because of the interference between the two waves

The *detector* is an ordinary type of *pentode grid* demodulator.

A *low-pass or band-pass filter* is employed, depending *upon the* kind of Doppler beat that is *desired* The low-pass filter is of a simple π type, having a cutoff frequency of 500 cps, the band-pass filter has a twin T circuit, the *mean frequency* of which varies around 1,000 cps *The Q is 3 to 5*

The amplification of the amplifier is 60 to 80 decibels

This *instrument* scarcely detects mechanical vibrations, such as those of the heart sounds and breath sounds, or of the external sounds (Satomura, 1957) Therefore, when *it is applied to the* heart, it records only the *pulse due to the* Doppler effect

An *audiophone* and an *oscilloscope* are used as monitors

The *recorder* is an *electromagnetic oscillograph*, transcribing the pulse on a film moving with a speed of 200 mm/sec The Doppler *beat is* recorded simultaneously with *phono*cardiogram, ECG, and other cardiovascular periodic phenomena.

When this method is applied to a subject in the recumbent position, a transducer is applied to the precordium (Fig. 4-256B). Fluid paraffin is employed to ensure *intimate* contact between the skin and the transducer. *The Doppler signal* can be obtained in any area in which the heart approaches the chest wall (Yoshida et al, 1961). *However*, the ultrasound is not transmitted through *bone tissue*, and, when the transmission occurs through the lung, the *ultrasound is weakened* because it is partly absorbed by the air. This occurs more often in stout subjects with a broad chest. In such cases, it becomes necessary to intensify *the power* of the signal or to use a signal with a longer wavelength.

The reflecting target on or within the heart changes according to the location of the transducer, resulting in different signals. Therefore, in order to get comparable data, it is best always to use *the same site for the* transducer. This is particularly true when attempting to receive the Doppler beat due to the motion of a valve. A definite site exists for the study of each valve.

The Doppler pulses are recorded as vertical vibrations *of the beam of the oscillograph* As shown *by Eq (3), there is no pulse* when the target does not move and the base line is steady. Moreover, if the target moves in a direction perpendicular to that of the ultrasonic beam, there would be no pulse However, this *occurrence* is unlikely.

There are several types of Doppler signals caused by the heart beat. The use of an oscilloscope and of an audiophone makes it possible to detect and roughly differentiate these various signals.

[illegible]

The Doppler signals due to the *motion* of the heart *have been classified* into the following types, according to frequency, time of development, duration, etc (Yoshida et al., 1961). (1) low-pitched *signal*, below 500 cps (mostly 100 to 200 cps); (2) high-pitched *signal* of about 1,000 cps, (3) irregular noise during systolic ejection and the rapid-filling phase of diastole The filter is used to record one or the other of these types of signals.

The *low-pitched signals* consist of systolic, early-diastolic, and presystolic parts *(Fig. 4-257)*. The systolic part *begins 0.04 to 0.09* sec after the Q wave, at about the same time as the beginning of the 1st heart sound, and lasts nearly until the peak of the T wave. The early-diastolic part begins almost *simultaneously* with the 2d heart *sound* and lasts for about 30 sec,

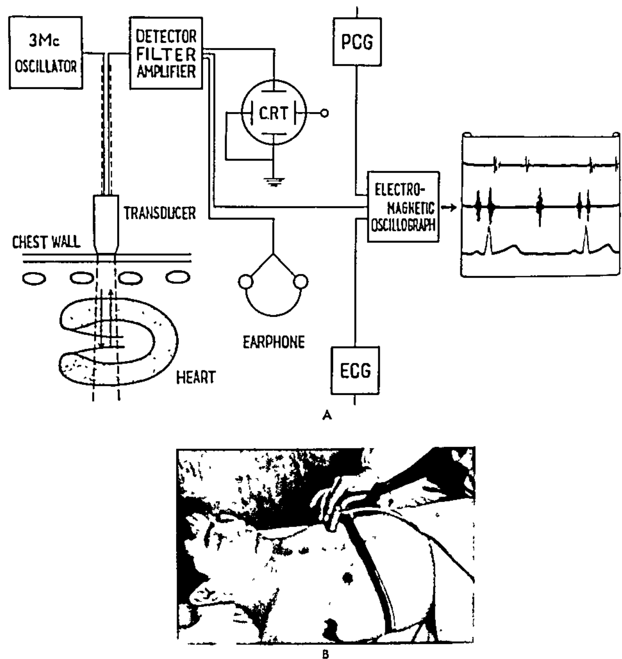


Fig. 4-256. Instrument for application of ultrasonic Doppler method to study of the heart. A. Schematic block diagram B. Application of transducer.

Hence, if the reflected wave is detected together with the initial wave from the source, a pulse appears, having a frequency fd of

$$fd = f \sim f' = \frac{2\mu \cos\alpha}{c - 2\mu \cos\alpha}$$

$$f = \frac{2\mu \cos}{c} f = \frac{2\mu}{\lambda} \cos\alpha \qquad (3)$$

Thus *the frequency of the Doppler beat is proportional to the velocity of the target.* This affords information about the existence and velocity of the target, which can be used for detecting the type of motion (Satomura, 1957).

Application to the Study of the Heart. When the ultrasound enters the human body through its surface, a part of it is reflected from the boundary between two living tissues, which possess different acoustic impedances. In the case of the heart, reflection occurs at the epicardial and endocardial surfaces of the free wall, septum, and valves. Edler and Hertz attached great importance to the reflection of the sound at the tissue-blood boundary. The reflected wave undergoes Doppler effect because of the motion of the heart. Then a suitable pickup receives a pulse having a fre-

Fig. 4-258. High-pitched Doppler signal related to the motion of the valves A Doppler signal related to the motion of the aortic valve Ao, opening, Ac, closing B Doppler signal related to the motion of the mitral valve Mc, closure, Mo, opening; Mps, presystolic signal.

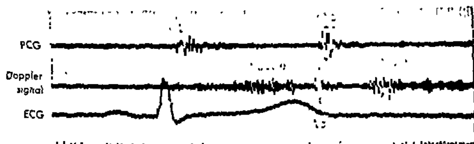


Fig. 4-259. Doppler heart noise, in systole and diastole Ac, aortic closure

so that this continuous noise is eliminated in order to record the snapping Doppler beats due to valvular motion

The interpretation of the high-pitched signal is supported by findings on the exposed dog's heart (Yoshida et al, 1960) the signals obtained by applying a transducer on the surface of an exposed dog's heart correspond to those obtained in man in regard to timing and duration Such signals can be obtained separately for each valve, for the semilunar valves, the area is limited and the direction of the ultrasonic beam has to be carefully selected. If the transducer is directly placed on the cardiac surface, the noisy beat becomes loud When it is moved from the pulmonic conus to the pulmonary artery, the snapping beat due to the motion of the pulmonary valve can be obtained only with a certain direction of the beam

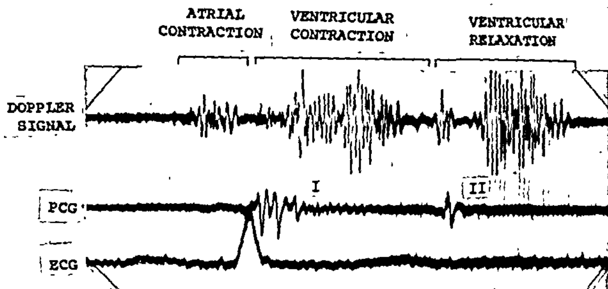


Fig. 4-257. *Low-pitched Doppler signal (transducer placed on the 4th left intercostal space at the parasternal line) related to the motion of the cardiac walls.*

These signals are evidence that the target moves with a speed of several centimeters per second, similar to that of the heart within the thorax. These systolic and early-diastolic parts have been interpreted as the result of the motions of the heart wall in systole and diastole, respectively The presystolic part begins 0.08 to 0.13 sec (mostly 0 10 to 0 11 sec) after the beginning of the P wave, and lasts for 0 07 to 0 12 sec. The timing and duration of this signal are similar to those of the 4th (atrial) sound This part has been interpreted as the result of the motion of the heart wall that accompanies the atrial contraction.

The *high-pitched signals* appear in early systole and again at the end of the T wave, they are brief, lasting 0 02 to 0 04 sec (Fig 4-258A, B). On the basis of the frequency of the signals and Eq (3), it can be seen that the targets move several times faster than the heart wall but only for brief periods of time, in early systole and at the end of systole Considering these data, the interpretation has been that the signals originate in a valve (or its chordae and papillary muscles)

The high-pitched signals are classified in two groups One of them is obtained at the base. in normal subjects, the first signal begins 0 09 to 0.13 sec after the Q wave, the second, at the end of the T wave. The latter appears just prior to the 2d heart sound, and terminates at the beginning of the main part of this sound In cases with splitting of the 2d sound due to bundle branch block or other cause, a high-pitched signal occurs before each component of the 2d sound, and its termination coincides with the beginning of the component itself. These data are evidence that the target reflecting this signal is closely related to the tension or vibration of *the semilunar valves* and their adjacent tissues, both at the time of opening and at the time of closure

Another group of signals is obtained in the apical area and consists of two signals, one beginning about 0 03 to 0.08 sec after the Q wave, and the other beginning 0 05 to 0 10 sec after the beginning of the 2d heart sound This group has been explained as the result of the motion of *the atrioventricular (AV) valves*. The interpretation was based on the time of appearance, the position of the transducer, and the time relationship between this group of signals and the other, related to the semilunar valves.

Thus, it is concluded that *the high-pitched Doppler signal is due to the motion of the valves and that the time of its development indicates the time of the motion of the valves*

The third phenomenon, i.e., the *continuous noise* (Fig 4-259), can be explained as a Doppler phenomenon due to blood flow (Kato et al). It lasts longer than the Doppler beats due to the valves and is generally weak, though it may occasionally become stronger It is easily differentiated from a snapping Doppler beat related to valvular motion by means of an audiophone For practical purposes, it is necessary sometimes to change the direction of the beam

The duration of isometric contraction in normal subjects is 0.03 to 0.08 sec. Since the completion of *Ac* and *Pc* coincides with the beginning of the 2d heart sound (II) or its components, it is convenient to measure isometric relaxation from the beginning of the 2d heart sound (or its components) to the beginning of *Mo* (or *To*). This phase (II to *Mo*) in a normal subject is 0.05 to 0.10 sec (mostly 0.06 to 0.08) and is slightly influenced by the heart rate.

Timing of the motion of the valves permits study of the duration of the various phases of the cardiac cycle both in normal subjects and in clinical cases. The advantages of the ultrasonic Doppler method applied to the heart are the following.

1. It is possible to detect the exact time of motion of any single valve without time lag.
2. The onset and completion of the motion of each valve are separately detected.
3. It is possible to record the exact time of the opening of the AV valves. The relationship of this opening to other phases of the cardiac cycle shows marked variations in various conditions.
4. It is possible to study separately the cycles of the left and of the right ventricle.
5. The method is relatively easy and completely devoid of hazards or discomfort for the subject.

CLINICAL APPLICATIONS

The high-pitched signal seems to be more important than the low-pitched for practical use. The time of motion of the valves, detected with this method, shows definite changes in various clinical conditions. The most important findings can be summarized as follows (Yoshida et al, 1961).

In myocardial lesions of the left ventricle (as in *hypertension* or *coronary heart disease*), *the opening of the mitral valve is delayed in comparison with that of normal subjects*, and the time interval from the end of the T wave to the opening of the mitral valve is prolonged. In such cases, the time interval from the closing of the aortic valve to the opening of the mitral valve is also prolonged, isometric relaxation (II to *Mo*) lasts more than 0.10 sec (mostly 0.12 to 0.14 sec) and occasionally reaches 0.18 sec (Fig. 4-260). This finding often occurs prior to development of electrocardiographic abnormalities. Isometric relaxation becomes shorter again when heart failure develops.

In *pure mitral stenosis* (Yoshida et al, 1961), the opening of the mitral valve occurs early and *the isometric relaxation of the left ventricle is shorter* (Fig. 4-261). This is probably because of the higher pressure difference between left atrium and left ventricle. *The time interval between the beginning of the Q wave and the closure of the mitral valve is prolonged* in mitral stenosis. *Mps* is usually absent, *Tps* is present.

In *right ventricular overload*, the tricuspid valve tends to open late.

In *atrial fibrillation*, changes of various time intervals are found. The time of closure of the AV valves is influenced by the preceding R–R interval: the longer the preceding R–R, the shorter the duration from the Q wave to the onset of mitral closure (Q to *Mc*). Variations of the time of motion of the valves are demonstrated, not only in pathologic conditions, but also in normal subjects during exercise.

The relationship between opening of the mitral valve, closing of the aortic valve, and electrical events is rather complex (Fig. 4-262). It can be described as follows. (1) *late opening of the mitral valve* (prolongation of isometric relaxation) is found in coronary heart disease, hypertensive heart, etc.; (2) *early opening of the mitral valve* (shortening of the isometric relaxation) is found in mitral stenosis, (3) *early closure of the aortic valve* occurs in *Hegglin's syndrome*, (4) late opening of the mitral valve may be accompanied by early closure of the aortic valve, (5) when the aortic valve closes early, opening of the mitral valve also occurs earlier (before the end of the T wave).

The time relationship between heart sounds and valvular motions studied by means of the ultrasonic Doppler method is of very great interest.

The beginning of the main part of the 2d heart sound coincides with the completion of closure of the semilunar valves (Fig. 4-258A). When the 2d heart sound is split, the two components have a definite relationship with the motions of the two semilunar valves.

The main component of the 1st heart sound begins at about the completion of the closure of the AV valve, which closes earlier; the early

NORMAL SUBJECTS. IDENTIFICATION OF THE SIGNALS OF EACH VALVE

The closing of the aortic and of the pulmonary valves is separately detected in subjects with bundle branch block and in those with a split 2d heart sound. Such cases allow the study of the best site for placing the transducer for separate detection of the aortic and pulmonary valve signals.

Most subjects with mitral stenosis and most of those with myocardial lesions of the left ventricle have either a delay or an earlier onset of the opening of the mitral valve. For example, in *mitral stenosis*, a high-pitched Doppler signal appears just before the opening snap, so that the snap occurs in the middle of the Doppler signal. This signal is evidence of *the opening of the mitral valve*. Another signal appears somewhat later than the mitral signal and has been interpreted as corresponding to *the opening of the tricuspid valve* The time of motion of the mitral valve is further separated from that of the tricuspid valve in right bundle branch block. On the basis of such findings, the site of application of the transducer for detecting the signals of either the mitral or the tricuspid valve has been determined

The best sites thus determined for the various valves are as follows (Yoshida et al, 1961): in the 4th or 3d left intercostal spaces near the margin of the sternum, *for the aortic valve, in the 3d* or 2d left intercostal spaces near the margin of the sternum, *for the pulmonic valve* (the semilunar valves are such small targets that it is necessary to adjust carefully the direction of the ultrasonic beam in order to obtain their signals). in the 4th left intercostal space at the parasternal line, *for the mitral valve* (the beam should be directed somewhat cranialwards), at the left lower sternal margin, *for the tricuspid valve* (the beam should be directed somewhat medially)

In general, each valve is identified according to the site of best detection of the signal, the time of development and properties of the signal, and the correlation between the signal and the waves of the ECG and phonocardiogram. The signal due to opening of the aortic valve *Ao* in a normal subject begins 0 09 to 0.14 sec after the beginning of the Q wave (Fig. 4-258A). The signal due to the opening of the pulmonic valve *Po* begins 0.09 to 0 13 sec after the Q wave. If only one signal due to the semilunar valves is obtained, it may be difficult to decide whether both valves move simultaneously, or only one of the two valves is detected. On the other hand, the signal due to either valve is easily differentiated in bundle branch block and in split 2d heart sound.

The signal due to closure of the mitral valve *Mc* in a normal subject begins 0 03 to 0.08 sec after the beginning of the Q wave (Fig. 4-258B). The signal due to the opening of the mitral valve *Mo* begins 0.05 to 0.10 sec (mostly 0.06 to 0.08 sec) after the beginning of the aortic 2d heart sound, and this interval is slightly influenced by the heart rate. The duration of the signal is 0.02 to 0.04 sec.

The tricuspid valve seems to move almost simultaneously with the mitral in normal subjects. However, the signal due to closure of the tricuspid valve *Tc* may precede or follow that of the mitral in some cases. Occasionally, it is difficult to identify *Mc* and *Tc* in normal subjects while it is easy to do so in subjects presenting alterations in the timing of either valvular motion.

In regard to the AV valves, besides *Mc, Tc, Mo,* and *To,* other high-pitched signals (*Mps* and *Tps*) appear in presystole. They begin approximately at the same time as the atrial or 4th sound and consist of low-pitched signals which occur 0 10 to 0 13 sec after the beginning of the P wave. In *complete AV block*, *Mps* and *Tps* follow the P wave but have no relationship to QRS; they disappear in cases *with atrial fibrillation.* In *mitral stenosis,* Mps is usually absent while *Tps* is present. These findings have been explained as indicating that they are due to a motion of the AV valves that is caused by blood flow into the ventricles at the time of atrial contraction. *Mps* and *Tps* disappear in severe tachycardia.

The time of opening and closing of the valves thus detected enables one to measure the duration of isometric contraction and of isometric relaxation. The duration of the *isometric contraction of the left ventricle* is defined as the interval from the beginning of closure of the mitral valve to that of opening of the aortic valve, i e., *Mc* to *Ao*. The duration of *isometric relaxation of the left ventricle* is defined as the interval from the beginning of *Ac* to that of *Mo*. Similarly, the duration of *isometric contraction* and that of *isometric relaxation of the right ventricle* are respectively measured as *Tc* to *Po* and *Pc* to *To*.

low-pitched vibrations of the 1st heart sound occur before closure of the AV valves

In mitral stenosis, the *opening snap* begins during the second half of the opening motion of the mitral valve (Fig 4-261). This relationship is different from that occurring between the 2d heart sound and the closure of the semilunar valve, and from that existing between the main component of the 1st heart sound and the closure of the AV valves.

The 3d heart sound occurs after a certain interval from the opening of the AV valves.

The relationships found between the heart sounds and the motion of the valves may give useful information regarding the contribution of valvular motions to the causation of the heart sounds

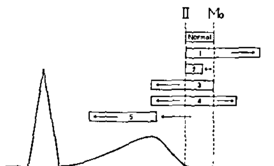


Fig 4-262. Time relationships between opening of the mitral valve Mo, 2d heart sound (II), and the end of the T wave. 1, Delayed opening of the mitral valve; 2, early opening of the mitral valve, 3, early 2d heart sound, 4, coexistence of 1 and 3, 5, markedly early occurrence of the 2d heart sound and early occurrence of mitral opening.

A
PCG
Doppler signal
ECG
I
II
Mps
Mc
Mo

B
PCG
Doppler signal
ECG
Tps
Tc
To

Fig. 4-260. Motions of the AV valves in myocardial damage. A. The opening of the mitral valve *Mo* is delayed. B. The opening of the tricuspid valve *To* is not delayed. *Mps*, presystolic signal of flow through mitral valve, *Mc*, mitral closure; *Tps*, presystolic signal of flow through tricuspid; *Tc*, tricuspid closure.

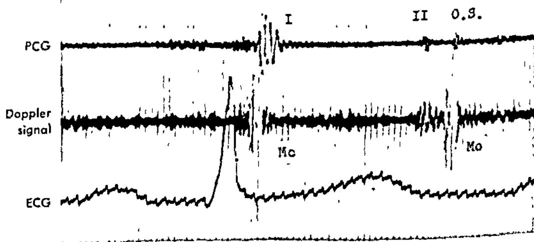


Fig. 4-261. Motions of the mitral valve in mitral stenosis. *Mps* (presystolic signal through mitral valve) is absent. *Mc* (mitral closure) is slightly delayed. II to *Mo* (mitral opening) is shortened. The opening snap OS begins while *Mo* develops.

Pribram (1926) and Wilson (1931) attempted similar procedures but failed. It is obvious that the inside of the cardiac chambers, filled with blood, could not be visualized with such simple instruments.

T. Sakakibara (brother of the author) was the first to observe clearly the inside of the heart (1936). He developed a cardioscope which spurted saline solution from its tip in order to dilute the blood (Fig. 4-263). He not only observed the inside of the heart in dogs and human beings, but also recorded the valvular movements and the muscular contraction of the heart of the dog on film. He also used this cardioscope to operate on two patients with mitral insufficiency, but without success.

Keith and Wappler (1942) designed an instrument that utilized a glass displacement chamber placed over a thoracoscope with a lens at a right angle. Aware of the inherent difficulties in small-field contact visualization, Harken and Glidden (1943) tried to enlarge the field of vision by placing a clear plastic balloon over a light-bearing thoracoscope. After being inserted in a collapsed state into the atrial appendage, the balloon was inflated with 8 to 15 ml saline solution. When distended, the balloon came into close contact with various structures.

Bloomberg (1950) described a cardioscope in which a stream of clear fluid was injected under pressure in order to wash out the blood for visualization of a relatively large field inside the heart. The principle of his cardioscope is the same as that of T. Sakakibara. Bloomberg was able to take photographs of the inside of the intact dog heart.

Murray (1950) described a contact type of cardioscope. Butterworth (1951) and Bailey and Bolton (1954) published their reports on cardioscopes made of methylmethacrylate (Fig. 4-264).

These cardioscopes converge the light originating either in the handle or near the tip, give a bright visual field, and are easy to manipulate. They have the disadvantage that blood streaming between the tip of the cardioscope and the area to be examined often obscures the visual field.

The Author's Cardioscope. Several cardioscopes were tried in order to improve T. Sakakibara's device. The following points must be considered:

Fig. 4-263. Tooru Sakakibara's cardioscope (saline-ejecting type, 1936).

Fig. 4-264. Bailey's cardioscope.

1. The blood must be removed between the object and the lens.
2. The diameter of the device must be reduced to a minimum.
3. Since one cannot follow exactly the rapid motions of the heart, a film record must be made for accurate analysis. This requires clear and wide vision and bright illumination.

In order to solve the first problem, the following two measures were taken:

1. A transparent substance was interposed between the lens and the object. A cardioscope with a rubber balloon and a vinyl chloride cap was devised for this purpose (Fig. 4-265). (Harken had carried out similar experiments in animals in 1943.)

2. A transparent substance was substituted for interposed blood. The method, however, is rather dangerous. A method of infusing saline solution into the heart for a short period without causing change of the heart action was further devised (see below).

The second problem was solved, though not in a completely satisfactory way, by the construction of a new type of cardioscope.

1

Cardiac studies with the cardioscope

SHIGERU SAKAKIBARA

At present, open heart surgery permits direct observation of the inside of the heart during operation. However, when a cardiotomy is performed after interruption of blood flow, the interior of the heart undergoes changes in comparison with a beating heart filled with blood, and certain physiologic phenomena cannot be clearly studied. It is important to observe the actual behavior of the beating heart in the normal conditions, i.e., filled with blood. The ability to do so would be valuable to cardiac surgeons, especially when they operate in cases of valvular disease. Even though exact knowledge of the heart action is necessary, few methods have been developed that can give adequate information. The cardiac valves open and close passively following changes of pressure in the ventricles, atria, and great vessels. The opening and closing of the valves so far has been deduced only by the use of intracardiac pressure curves. Other methods cannot give accurate information about valvular motions, and post-mortem examination cannot reveal the movements of valves in the living organ.

How do the valves, chordae, and papillary muscles act during the contraction of the heart and the changes in intracardiac pressure? To what extent do the valves open and close, and how much blood is ejected? Though a direct observation of these movements is necessary in order to solve certain dynamic problems, such studies have been few so far, because of technical difficulties. Almost all previous studies have revealed the external motions of the heart by means of roentgenologic, volumetric, or suspension methods. McMillan reported relatively accurate observations of the valvular actions by studying them in hearts connected to a pump while simultaneous tracings of intracardiac pressures were recorded. However, the myocardium and vascular walls did not contract spontaneously and there was some difference in comparison with physiologic valvular motions in a living body.

In order to study the inside of the living heart, the author has built a *cardioscope*, which makes it possible not only to observe but also to take moving pictures of living hearts under nearly physiologic conditions. This cardioscope has been employed prior to cardiac operations. It is still in an experimental stage, and more study is needed before its final release to other workers in the field.

Historical Aspects of Cardioscopy. Rhea and Walker were the first to report on a cardioscope. However, their instrument, for technical reasons, allowed only a poor visibility.

Allen and Graham (1922) reported on an instrument with which they studied the heart chambers. Their cardioscope was a metal tube provided with a lens and a source of light at one end. The valve leaflets were visualized by holding the cardioscope in such a way that they came in contact with the lens during systole. A valvulotome was at the outside of the tube of the cardioscope, and its blade was at a right angle to the handle while the cutting edge faced the lens. The entire blade was placed in a groove cut across the center of the lens.



Fig 4-267. Cardioscope for aortic commissurotomy A A knife with a serrated edge is fixed at the tip B This knife can be covered when the cardioscope is inserted.

In experiments carried out in dogs, clamps were placed on the superior and inferior vena cava and pulmonary veins, simultaneously saline solution was injected into the left auricle under pressure of 30 cm of water during cardioscopic observation (Fig 4-268) No interference with the action of the heart was observed during this procedure for 1 min Slight modification of the peripheral flow, if observed, could be overcome immediately by discontinuation of the procedure No changes were seen histologically even after intermittent 6-min irrigation with interruption of the blood stream However, as a 1-min observation is not sufficient, the following method was devised

Two dogs were anesthetized and cannulas were introduced into both femoral arteries of one animal One cannula was connected to a Y tube, and No 100 polyethylene tubes were attached to both These tubes were inserted into the right coronary artery, circumflex branch, and anterior descending branch of the left coronary artery, which were perfused by the other dog (Fig. 4-268)

After completion of the coronary bypass, the blood flow into the heart was interrupted, the pulmonary arteries were ligated at the hilum, and venous blood was drained from the right atrium Then the heart was irrigated with normal saline solution Normal saline solution flowing into the aorta was drained via the femoral artery through the inserted cannula at a level of 60 cm above the body level and a minimum blood pressure of 40 mm Hg was maintained Thus, prolonged observation (30 to 40 min) with saline irrigation was possible without interfering with the heart beat Electrocardiograms and intracardiac pressure curves were simultaneously recorded (Fig 4-268). Special marks on the tracing were synchronized with the turning on and off of the cardioscopic bulb, and comparative studies were carried out.

Five to ten seconds after interruption of the blood flow and irrigation with saline solution through the atrium, the heart chambers became clear Almost no change in the intracardiac pressure curve and electrocardiogram was observed for 1 min after interruption of blood flow. If blood circulation is reestablished after 1 min, the procedure can be repeatedly performed

However, more recently the author has prolonged the observation by maintaining the coronary circulation of one dog through cross circulation from a second dog

The motions of the valves are then compared

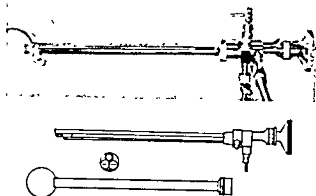


Fig. 4-265. Cardioscope with rubber balloon.



Fig. 4-266. Cardioscope used in visualization of mitral valve.

These methods can be used for the direct visual observation of the inside of the heart or for operative procedures in clinical cases. They also permit a record to be made on film of the interior of the heart in clinical cases (see below).

It is always necessary to infuse the heart with saline solution for a short time in order to observe the valvular motions.

Construction of the Cardioscope. The cardioscope is built as follows The optical tube of the cardioscope for general inspection is 226 mm long and 3.5 mm in outer diameter and has a bore of 3 mm The optical system consists of 12 parts and is provided with a wide-angle lens. The distance between the objective lens and the object is 16 mm, and the structures are seen in actual size As there is a fixed focus, the visual field is increased twice for every increase of 16 mm of distance

The cardioscope has two small light bulbs at its tip Each bulb has a diameter of 3 8 mm and a length of 15 mm, it is filled with argon and has 15 watts for an alternating current of 6 to 8 volts, and 40 watts for a current of 12 volts A second tube for flushing water is placed parallel to the main optical tube The solution flushed out of this tube is aspirated through a space which is between the flush tube, the optical tube, and the lamps, and the solution moves at a constant rate The diameter of the flush tube is 9 mm.

The cardioscope for the *observation of the mitral valve* has a diameter of 12 mm and a curvature, 30 mm from the tip, of 120°, so that it can be inserted from the left atrial appendage (Fig 4-266) The optical tube is 5 5 mm in diameter It contains three prisms and nine lenses. The flush tube is also used for aspirating the solution A rubber balloon is fixed on its tip. Saline solution is injected through the tube, inflating the balloon to the desired size The elasticity of the balloon makes it possible to keep the tip in close contact with the atrial or ventricular wall, the valves, or chordae tendineae. Close observation is possible, as the balloon moves together with the above structures. The tip is provided with outlets for ejecting saline solution to dilute the blood, so that the areas not in contact with the balloon can also be visualized.

The second model is provided with a vinyl chloride cap and was built for surgery of the mitral valve. Vinyl chloride is hard at normal room temperature but becomes pliable when warmed to body temperature and adheres closely to the heart wall The cardioscope used for operative procedures will be described below.

The cardioscope for commissurotomy of the aortic valve is similar to that used for observation (Fig 4-267). As described below, the serrated blade is placed on the outer surface of the tube and may be covered. A ring placed at the root of the outer tube can be moved back and forth, providing protection for the blade. The blade is 3 5 mm at the tip and end, and 1 5 mm at the center (see figure). The part with serrated teeth is 15 mm long, the over-all length is 30 mm

Recording and Analysis of the Valvular Actions. Studies of the motions of the valves recorded on films have been made by McMillan and Glover, but their investigations were carried out on the hearts of cadavers, to which a pump was attached in order to create intracardiac pressure changes. Therefore, these studies did not record the normal contraction and dilatation of the heart and vessels On the other hand, the author of this chapter was able to observe the physiologic action of the valves with his cardioscope. Although distinct observation is possible with the previously mentioned methods, minor details are difficult to record on film.

ECG
PCG
Aort. P.
Aur. P.
Vent. P.

Fig 4-269 Electromechanical correlation of mitral and aortic valve movements in the canine heart.

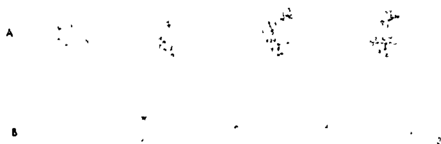


Fig. 4-270 The action of the mitral valve in the dog's heart A. The valve seen from the left ventricle B The valve seen from the left atrium The two-stage closure of the valve is clearly demonstrated

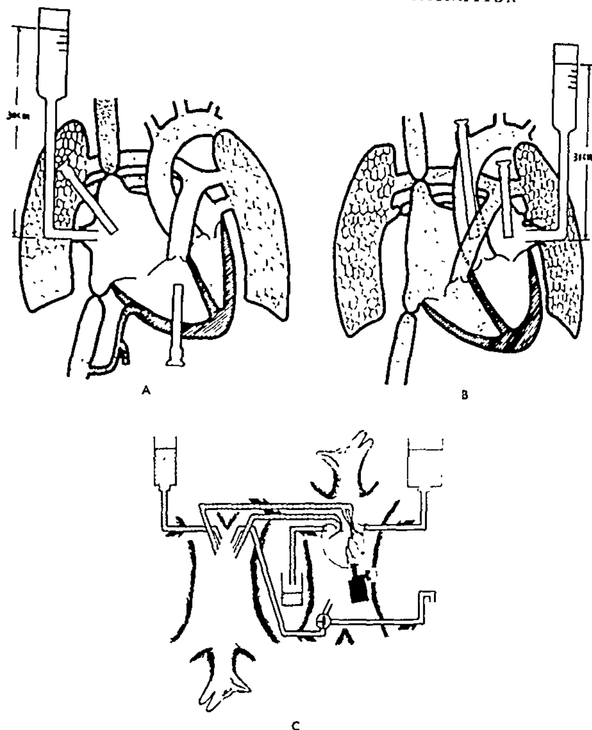


Fig. 4-268. Schematic drawing of method of blood occlusion and saline irrigation of heart. A. Irrigation of right side of heart The coronary blood from the sinus is conducted to the femoral vein by catheter. B. Irrigation of left side of heart C. Combined use of differential left ventricular perfusion with saline solution and cross circulation for coronary perfusion.

with simultaneously recorded electrocardiograms, phonocardiograms, and intracardiac pressure tracings (Fig. 4-269).

Mitral Valve. The movements of the leaflets, papillary muscles, and chordae tendineae, viewed from the left ventricle, are shown in Fig. 4-270A. At the beginning of diastole, the ostium opens completely while the chordae attached to edges of the leaflets slacken for a moment.

A gradual, partial contraction of the ostium then occurs, followed by a sudden closure, probably caused by retraction of the fibrous ring because of pressure exerted at the base of the leaflets. The two-stage closure of the valve is clearly seen from the atrial side (Fig 4-

leaflets upwards Then, during the P wave of the ECG, an elevation of atrial pressure occurs, and the orifice becomes larger. Soon after the peak of QRS, the ventricular pressure is abruptly increased and the valve closes at the beginning of isometric contraction, simultaneously with the beginning of the 1st sound During the middle of systole, at the peak of the T wave, the valve bulges toward the atrium and the commissures are lifted upward

Aortic Valve. The motions of the aortic valve are completely different from those of the mitral valve. Figure 4-271 shows the valvular action viewed from the ventricle The root of the aorta expands at the beginning of ventricular contraction

Pulmonary Valve. The movements of the pulmonary leaflets are almost identical to those of the aortic, except that the valvular opening is more nearly circular, probably on account of the smaller degree of pressure exerted on the valve (Fig 4-272A).

Tricuspid Valve. The appearance of the tricuspid valve, both open and closed, is shown in Fig 4-272B. The two-stage closure is less marked than for the mitral valve.

270B). The chordae tendineae attached to the edge of the leaflets slightly relax at the opening of the valve but become tense immediately afterwards. The motion of the anterior cusp is greater, while that of the posterior cusp is far smaller. When blood or saline solution flows from the atrium into the ventricle, *it moves* first toward the apex and then back toward the base, so that the leaflets are pushed upward at the end of the diastole, with *marked narrowing* of the AV orifice. The valvular opening *during life is much smaller than that observed* in the cadaver; the maximum opening is *only* about one-third of the actual complete opening. *As the papillary muscles begin to contract* in early systole, the chordae tendineae prevent *any eversion of the leaflets* toward the atrium.

The opening of the mitral valve occurs after *the end of the* T wave on the ECG, just after *the end of isometric* relaxation. When the ventricles begin their diastole, the chordae tendineae relax for a moment through relaxation of the papillary muscles. Then the free edges *of the* cusps start to open slightly after the closure of the aortic valve. Later on, the mitral valve reaches its maximum opening, the left *ventricle* reaches its largest size, and the papillary muscles are distended, so that the chordae become tense At about the middle of the *T–P interval*, when the ventricular pressure is equal to atrial pressure or slightly lower, the free edges move toward the center of the ostium, assuming the form of a cylinder, because of a minor backflow which pushes the



Fig. 4-271. The action of the aortic valve in the dog's heart A The valve seen from the left ventricle B The valve seen from the aorta

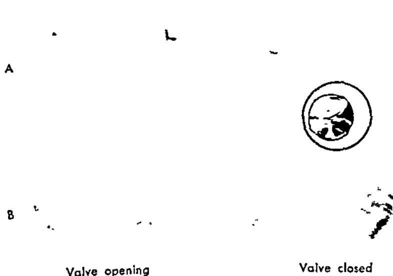


Fig. 4-272. A. The action of the pulmonary valve in the dog's heart The valve is seen from the right ventricle. B. The action of the tricuspid valve in the dog's heart.

specimens, independent of urine volume, occur only in severe organic renal disease. Polyuria and *nocturia* with very low *specific gravity* (1,001 to 1,003) suggest *diabetes insipidus* but may also be caused by "kaliopenic nephropathy," as a result of depletion of body potassium by diarrhea or by primary aldosteronism. Lack of response to pitressin and reversibility by potassium repletion differentiate this hyposthenuria from that of diabetes insipidus (Schwartz et al; Conn et al; Relman et al.; Dustan et al) Hyposthenuria occurs also in *sickle-cell anemia* (Keitel et al.) and in *primary hyperparathyroidism* (Cohen et al.) Polyuria and nocturia with high specific gravity should raise the suspicion of diabetes mellitus

As long as kidney function is maintained, urine is highly concentrated and deep amber-colored in acute oliguria This is true regardless of whether the oliguria is due to inadequate fluid intake, extrarenal water loss (such as sweat), vomiting, diarrhea, prerenal water deviation (as in edema formation), cardiac failure, nephrosis, or hypotension (hemorrhage or myocardial infarction) The common denominator in all these conditions appears to be the decrease of blood volume, renal blood flow, and glomerular filtration rate, leading to sodium retention by the kidney and causing the excretion of a sodium-free, yet highly concentrated urine, a characteristic finding in the frequently associated acute extrarenal azotemia (Rosenblum) However, with prolonged duration of the circulatory renal insufficiency (for instance, following prolonged shock), concentrating ability of the tubules may be lost for varying periods of time, and pale-yellow urine with specific gravity of about 1,010 will be excreted despite persisting oliguria Such tubular dysfunction may be engendered by acute *tubular necrosis*, then the period of hyposthenuria-oliguria is followed by a "diuretic phase," a period of polyuria, hyposthenuria, and increased sodium loss, and finally by a slow return to normal tubular function with restoration of concentrating ability (Strauss, Burch et al, Bull, Merrill)

DIAGNOSTIC SIGNIFICANCE OF URINE COLOR

A few physiologic and clinical data appear necessary to emphasize the diagnostic significance of relating urine color to both volume and kidney function The color of normal *urine* is due largely to *urochrome* and, to a much lesser extent, to *uroerythrin* and *urobilin*. In general, daily excretion of the main urinary pigment, urochrome, is constant and roughly proportional to individual metabolic rates (Drabkin; Ostov et al.; Vorzimer et al., Moreland et al.). Hence color intensity of the urine is inversely proportional to volume.

In the oliguria of cardiac failure, however, not only is urochrome more concentrated, but its absolute excretion is increased (Heilmeyer), thus contributing largely to the dark color of the urine of such patients. The source and chemical constitution of urochrome are still unknown. Evidence that urochrome is derived from blood pigments, that it consists of various dipyrrole (mesobilifuscin) fractions, and that its increase in cardiac failure, therefore, reflects enhanced hemolysis (Heilmeyer et al.; Stich; Stich et al), conflicts with statements that it contains no pyrrole compounds (Fischer et al; Rangier et al, 1938) and that it is composed of a mixture of amino acids and melanin or melanin-forming compounds (Radsma et al.). Liver dysfunction has also been suspected as cause for augmented excretion (Weiss).

Since the pigment is not demonstrable in the blood, the final elaboration of urochrome from colorless precursors in the blood is assumed to occur by an oxidative process in the kidney (Becher, Heilmeyer) Impairment or abolition of this process in severe renal damage is held responsible for the pale, watery color of the urine that clearly differentiates the oliguria of late renal disease from that of uncomplicated cardiac failure

Uroerythrin, a pinkish-red compound probably similar in composition to urochrome (Radsma et al.), accounts for 10 to 15 per cent of the normal urine color (Heilmeyer) and is also present in higher amounts in cardiac failure It is commonly precipitated with and absorbed to uric acid and monourates, causing the brick-red color of the *precipitate* (*sedimentum lateritium*). Uroerythrin excretion also depends on adequate kidney function (Stepp), so that the presence of a brick-red-colored sediment, frequently seen in congestive heart failure, can serve as an indication for maintained renal function and against extensive renal involvement

Urobilin, an orange-colored oxidation product of the colorless, unstable urobilinogen, con-

Urinalysis in cardiovascular disease

RICHARD STERNHEIMER

The value of urinalysis in diagnosis and differential diagnosis of cardiovascular-renal disease depends upon its correlation with the patient's history and clinical findings. The widely practiced "routine examination" of a casual specimen yields only limited information. Composition of the urine varies greatly with its volume, and both are affected by the patient's fluid intake, diet, temperature, and insensible water loss. Nutritional imbalance, salt depletion, and dehydration, frequently observed in patients with cardiac disease, may influence renal function so markedly as to produce urinary changes resembling those of renal disease (Sargent et al.) While these factors are generally recognized, they are often not taken into account in the interpretation of urinary findings; as a result, diagnostic error may occur

GENERAL OBSERVATIONS

Urine volume, specific gravity, and *color* should be evaluated together, in separate determinations of 12-hr day and night excretion Normally, urinary volume, as well as the amount of sodium, potassium, and chloride excreted, is from one and one-half to three times greater during the day than at night, the concentration of these electrolytes and of nitrogenous end products and the specific gravity are greater in the smaller night volume (Manchester; Boret et al ; Sirota et al ; Goldman, Stanbury et al ; Papper et al.).

This *diurnal rhythm* of renal excretion of water and electrolytes is reversed in cardiac failure and in cirrhosis of the liver, in which the day volume may be one-third to one-half that of the night volume (Baldwin et al ; Goldman et al.).

The *nocturia* of congestive failure is associated with *oliguria,* a corresponding *high specific gravity* (1,025 to 1,030), and a deep amber urine color. Despite the high specific gravity, 24-hr excretion of sodium and chloride is characteristically diminished. Recovery from cardiac failure is heralded by rising urine volume, a proportional decrease in specific gravity and color intensity of the urine, increased sodium and chloride excretion, and return to the normal rhythm of excretion. Loss of the diurnal rhythm is also noted in *Addison's disease* and forms the basis of the *Robinson-Kepler-Wilder test.* In contrast, the nocturia of advanced renal disease is characterized by high 24-hr urine volume, lower specific gravity, and lighter urine color, representing a *compensatory polyuria* for the decreased concentrating ability of the kidney (Volhard). Here water and solute excretion cannot proceed independently but urine flow is determined by the osmotic load (A G. White et al , Platt, Baldwin et al.). Polyuria and pitressin-resistant urinary hypotonicity (so-called "water-losing nephritis") may result (Roussak et al ; Kleeman et al). Fixation of specific gravity around 1,010 (*isosthenuria*) and pale urine color in all

infrequently is enhanced by dehydration, accelerated protein catabolism, intestinal paralysis, and increased intestinal putrefaction, indican excretion is not impaired, and a marked *rise in urinary indican* may result. In differentiating *azotemia* complicating cardiac or cardiovascular disease from *true uremia, a strongly* positive indican test, therefore, points to the extrarenal origin of urea retention. If, in addition, *chloride* excretion in the urine, as determined by the simple *Fantus test*, is absent, and the *Ehrlich aldehyde reaction* or the "aldehyde reaction in the warm" are positive, the diagnosis of *extrarenal azotemia* can be made with confidence. These tests can be performed in less than 2 min and are of great practical *value in guiding the clinician in his therapy.*

Gross *hematuria*, manifested by bright-red, greenish-red, coffee-colored or "smoky" appearance of the urine, occurs as a complication of cardiac disease, usually in intermittent or episodic form. This is particularly true for *renal infarction*, caused by embolism from mural *thrombi in myocardial infarction or in mitral* stenosis with atrial fibrillation, or as a complication of nonbacterial thrombotic endocarditis (Wallach et al., 1954b, Regan et al) In *subacute bacterial endocarditis*, renal infarction is often difficult to differentiate from *focal embolic glomerulonephritis or diffuse glomerulonephritis, both of which may give rise to macroscopic* hematuria (Libman, Bell, Allen, Villareal et al).

In systemic vascular disease, *massive hematuria* is found with the necrotizing arteritis of malignant hypertension *secondary to nephrosclerosis*, pyelonephritis, glomerulonephritis, or obstructive arteriosclerosis (Schottstaedt et al , Allen, Corcoran et al) About 20 per cent of patients entering the malignant phase of essential hypertension evidence painless, gross hematuria (Golding et al) In rarer instances, symptomless gross *hematuria (so-called renal epistaxis)* may occur in essential hypertension. Occasionally, periarteritis nodosa (Spiegel, Ralston et al), systemic scleroderma, or systemic lupus erythematosus (Sheard et al) may cause macroscopic hematuria *Anticoagulant therapy* as a possible cause of hematuria should not be overlooked It is *important to realize*, however, that the great majority of conditions leading to gross hematuria is due to local infection, stone or tumor formation in the upper or lower urinary tract, or hematologic disorders

Microscopic urinalysis is indispensable, not *only in the differential diagnosis of these hematurias*, but also in differentiating them from *hemoglobinuria*, in which *urine color may* be pink-red, brown, or black. Absence of red cells or red cell shadows in the sediment, particularly *in* urines with specific gravities above 1,007, tends to rule out *hemolysis* in the urine as a source of the abnormal color, and speaks for true hemoglobinuria (Ham). Both hematuria and hemoglobinuria give positive chemical and spectroscopic tests for blood. The infrequent incidence of hemoglobinuria as a complication *of cardiovascular disease is largely* limited to renal infarction (Libman et al.) or to hemolytic transfusion reactions, shock, and ensuing tubular necrosis (Ross)

A "port-wine," pink, or red urine color, *especially if associated with a clinical syndrome* of hypertension, tachycardia, nervous disorders, and abdominal colicky pain, suggests *acute porphyria*. Urinary tests for porphobilinogen, coproporphyrin, and uroporphyrin will help to *differentiate this clinical picture from the closely* similar one of periarteritis nodosa or from renal infarction (Nesbitt, Schwartz et al , Watson). The various porphyrinurias, which frequently do not alter urine color, but sometimes *may, are rarely observed in cardiovascular disease* Increased coproporphyrin excretion has been described in *the first 2 or 3 days following* myocardial or pulmonary infarction (Escola et al)

PROTEINURIA

Proteinuria in a patient who has cardiac disease without intrinsic renal disease or hypertension is most commonly found in combined heart failure According to White, "the greater the congestion, the more the albuminuria " A *positive correlation of proteinuria with the degree* of heart failure has also been suggested by Race et al Such correlation, however, may be more apparent than real, since the degree of cardiac insufficiency is mostly mirrored by the concomitant oliguria, so that *the protein* concentration in a casual specimen may suggest a *higher-than-actual rate of 24-hr* excretion (Berglund et al). In gauging the results of therapy, quantitative protein determinations on 12-hr day and night urine specimens are needed

In general, the proteinuria *of cardiac failure* is moderate, usually below 1 Gm/liter (Race

tributes little to the color of normal urine, but may contribute significantly whenever urobilinogen excretion is increased. Normal daily urobilinogen excretion in the urine amounts to only 1.4 ± 1.1 mg (Zieve et al.). In congestive heart failure, daily values as high as 45 and 56 mg have been observed (Sherlock; Watson). *Urobilinogenuria* in heart failure is more frequent in patients with a palpable, tender liver, and is found particularly in rheumatic heart disease and atrial fibrillation. Yet, there appears to be no significant correlation between the size of the liver, the degree of failure, and the 24-hr urobilinogen excretion (Chavez et al.). Elevated values for urinary urobilinogen have been noted in acute myocardial infarction on the second and third days after the attack, and have seemed to be of value where other diagnostic evidence was inconclusive (Evans et al.; Watson).

Absence of urobilinogen in the urine under conditions in which increased urobilinogen would be expected strongly suggests advanced renal disease, provided that no antibiotics have been administered (some suppress the formation of urobilinogen in the gut)

The renal mechanism of urobilinogen excretion is controversial (With, Watson), but renal tubular participation appears likely (Royer et al.). Urobilinogen is rarely present, even in combined heart failure, when kidney function, as measured by urea and creatinine clearances, is below 20 per cent of normal Hence a positive urobilinogen reaction in a patient with cardiovascular-renal disease usually suggests absence of renal failure, as in shock, hemorrhage, or myocardial infarction.

Urobilinogen consists of a group of closely related compounds (mainly stercobilinogen, mesobilirubinogen, and *d*-urobilinogen), which reacts with *Ehrlich's reagent* to give a red color The red color produced on warming the urine with Ehrlich's reagent is due not to urobilinogen but to *indoxyl* (Goessner, 1948) This "aldehyde reaction in the warm" occurs in normal urine but is only rarely found in chronic renal insufficiency (personal observations), it may serve in the differential diagnosis of extrarenal azotemia and chronic uremia (see the discussion further on of indican).

Bilirubin, present only in traces in normal urine, appears to a variable degree in the *jaundice* of cardiac failure, most commonly in patients with mitral stenosis, particularly if the mitral stenosis is combined with *tricuspid incompetence* (Sherlock). It produces an orange-green to reddish-brown urine color and a yellow froth when the urine is shaken.

In cardiac disease, the increase in amount of serum and urine bilirubin and the associated liver dysfunction have been related to diminished hepatic blood flow (Myers et al), arterial hypoxia with reduced oxygen saturation in the hepatic vein (Evans et al.); tissue anoxia (Pick); increased venous pressure and hepatic engorgement (Paton et al; White et al.); and central necrosis or central and portal fibrosis of the liver (Moschkovitz, Katzin et al; Schalm et al.). In view of the frequent presence of pulmonary infarction, extravascular hemolysis has been considered a factor (Eppinger; Sherlock; Felder et al.), but jaundice and bilirubinuria in cardiac failure occur also without infarction (Parker et al.).

In the *bilirubinuria* of cardiac failure, levels of both indirect- and direct-reacting serum bilirubin are increased (Schalm et al). It has long been known that *indirect-reacting serum bilirubin* is poorly, if at all, excreted by the kidneys and that *direct-reacting bilirubin* appears readily in the urine. The difference in the behavior of the two pigments, with regard to both chemical reaction and renal excretion, is due not to different protein binding (Katskin et al.) but to conjugation, mostly by the liver but also by the kidney, of bilirubin with glucuronic acid, to form the water-soluble, readily excretable direct-reacting type from the poorly water-soluble, nonesterified indirect-reacting pigment (Schmid; Billing et al, Grodsky et al). Yet even direct-reacting bilirubin is not always excreted In renal insufficiency, urinary bilirubin may be absent despite concurrent jaundice with increased direct-reacting bilirubin (Peremy, With).

While *indican* does not affect urine color, it may, if its amount is increased, produce darkening of urine on standing The urinary indican test, unjustly discredited as of little clinical value, is useful in the differential diagnosis between extrarenal azotemia and chronic uremia. Indican is readily excreted and is concentrated in the urine to more than twenty times its blood levels by the normal kidney, but fails to be concentrated in the urine in advanced renal disease, thus producing the characteristic rise in indican blood levels (Becher et al.). In *extrarenal azotemia*, where indican formation not

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acting pigment ([illegible] et al). Yet even direct-reacting bilirubin is not always excreted. In renal insufficiency, urinary bilirubin may be absent despite concurrent jaundice with increased direct-reacting bilirubin (Peremy, With).

While *indican* does not affect urine color, it may, if its amount is increased, produce darkening of urine on standing. The urinary indican test, unjustly discredited as of little clinical value, is useful in the differential diagnosis between extrarenal azotemia and chronic uremia Indican is readily excreted and is concentrated in the urine to more than twenty times its blood levels by the normal kidney, but fails to be concentrated in the urine in advanced renal disease, thus producing the characteristic rise in indican blood levels (Becher et al.). In *extrarenal azotemia*, where indican formation not

In quantitative studies, either 10 *ml* of the amount voided in a *given time interval*—12 hr (Addis) or 3 hr (Hamburger et al, 1950)—is centrifuged at about 1,500 rpm, and after the supernatant has been removed, usually to 0 5 *ml* (with much sediment, more supernatant is required), the count of the various elements is *related to the urine volume* in the chosen time interval to yield excretion rates of formed elements *per minute*, hour, or 24 hr, or a varying *amount of urine equivalent to the excretion in the standard time period* (say ⅓ hr) (*Addis test*) is centrifuged and the count directly calculated to yield excretion rates for any of the chosen time periods The latter method is particularly suitable for comparative impressions in direct qualitative evaluation (Castaigne, Lippman)

The sample should be examined by the physician himself. No description, qualitative or quantitative, can replace his immediate visual impression, encompassing (by the scanning of various fields) the composite picture of the several formed elements More often than not, details considered insignificant by the unsuspecting technician may yield diagnostic clues to an observer whose eyes have been sharpened by knowledge of the patient's clinical picture

Diagnostically significant is the structure of casts *Hyaline casts* are related to proteinuria and its wide range of causes and are, therefore, least meaningful in differential diagnosis. In contrast, casts containing renal epithelial cells or their granular fragments (*epithelial casts, coarsely or finely granular casts*) point to the presence of renal tubular damage. The finding of doubly refractile fat in casts or renal epithelial cells is an indication of severe tubular damage, it occurs predominantly in the nephrotic *syndrome*, of whatever origin (glomerulonephritis, *amyloidosis*, *lupus* nephritis, intercapillary *glomerulosclerosis*, various poisonings), and serves to differentiate this group from *hypertensive* or arteriosclerotic renal vascular disease (Leiter). Increasing amounts of broad casts, considered to be caused by the combined effect of marked tubular dilatation and intrarenal stasis, portend severe renal impairment and have been aptly designated as *renal-failure casts* (Addis). Similarly, *waxy casts* are also found most frequently in advanced *renal disease*

Red blood cell casts denote renal hematuria and are characteristic of diseases associated with glomerulitis, such as glomerulonephritis, focal embolic glomerulonephritis, lupus nephritis, periarteritis, and progressive systemic sclerosis. In cardiac disease, it is important to remember that red cell casts are not found in simple congestive failure, so that their presence immediately points to renal complications, such as infarction or embolic phenomena in subacute bacterial endocarditis or in rheumatic valvulitis, focal suppurative glomerulonephritis in acute pyogenic forms of bacterial endocarditis; and complicating or unrecognized preexisting glomerulonephritis.

Although the importance of *early recognition* of renal involvement in bacterial *disease is well* known, the danger of overlooking preexisting renal disease in apparently simple congestive failure is often not realized. It is by no means rare that a physician, after having induced massive diuresis in a patient with congestive heart failure, is suddenly faced with rapidly rising *azotemia*, far surpassing, both in speed and degree, that seen in the low-salt syndrome. The finding of red blood cell casts under these circumstances will reorient diagnosis and therapy.

White blood cell casts most frequently suggest pyelonephritis, but they also occur in acute glomerulonephritis and in the nephrotic syndrome (Schreiner, 1957)

The "telescoped" *sediment* [so called because it contains the whole range of formed elements ordinarily seen separately in the various stages of glomerulonephritis, viz., red blood cells, red blood cell casts or blood casts (Addis), fatty, waxy, and broad casts, as well as doubly refractile fat bodies] is a characteristic finding in collagen diseases, *periarteritis* nodosa, scleroderma kidney, and lupus erythematosus (Krupp, Miale, Cole) It is, however, not pathognomonic (Schreiner, 1955, Hamburger et al ; Muehrcke et al , Kark).

Hematuria has already been discussed, from the microscopic standpoint, one should add that washed-out red cells, or *erythrocytic ghosts*, when found free in concentrated, fresh, acid urine specimens, suggest renal parenchymal origin, whereas *normal-looking*, hemoglobin-filled red blood cells are more likely to derive from other sources in the genitourinary tract.

For the various aspects of *pyuria*, observations on stained sediments become pertinent Of the *variety of stains* devised for easier recog-

et al.; Lenègre et al.); only on rare occasions does it reach 4 Gm, and very seldom even 10 Gm/liter (Volhard). As a rule, 12-hr values in the urine of patients with cardiac failure vary between 50 and 500 mg, but values up to 3 Gm do occur (Goldring). In rare instances, heavy proteinuria in prolonged cardiac failure may lead to a picture of cardiac nephrosis with hypoproteinemia, hyperlipemia, hypercholesteremia, and edema (Lenègre et al.; Squire, Squire et al.). Complete recovery from this nephrotic syndrome has been reported following reestablishment of cardiac compensation in *chronic constrictive pericarditis* (Blaney et al.). Proteinuria and edema, although frequently observed simultaneously, are not necessarily associated. Proteinuria may be absent in the edematous patient with cardiac disease and may be marked in the patient without edema (Volhard, Scheifly et al).

In the absence of right ventricular or combined heart failure, proteinuria is quite rare, except in *subacute bacterial endocarditis*, where it is almost invariably present, even when no glomerular lesions or infarcts are found (Friedberg). Here, 12-hr values range between 200 and 900 mg. In *acute rheumatic fever*, proteinuria is less marked (Goldring) With *renal infarct*, protein excretion is mostly intermittent, and its episodic character has been considered better evidence of renal infarction than red cells in the urine (Horder)

In the majority of patients with heart failure, the proteinuria is reversible, but it has a greater tendency to persist if cardiac insufficiency arises during hypertensive vascular disease Proteinuria in uncomplicated essential hypertension is variable and may range from normal values to 500 mg/12 hr. It may be absent for years, and even remain minimal, in cases terminating in renal insufficiency or uremia, or it may appear early in the disease and persist (Fishberg) But while the over-all incidence of proteinuria in uncomplicated hypertension is only about 20 per cent, it rises to 50 per cent in hypertensive patients with combined heart failure (Lenègre et al). Twelve-hour excretions may then be considerably higher, with a range between 100 mg and 2.5 Gm. In malignant hypertension, the degree of proteinuria may reach much higher values and seems to be closely associated with the level of arterial pressure (Piette et al).

The mechanism of proteinuria in cardiac failure is obscure. The factors to be considered are renal vasoconstriction and glomerular ischemia (Starr; Chesley et al.); reduction of glomerular filtration rate (Javitt et al), increased renal vein pressure (Wégria et al.), and increased diffusion of protein molecules (Govaerts et al.), or changes in "molecular sieving" (Pappenheimer) as a result of slowing of glomerular circulation. Changes in glomerular permeability and filtration rate, however, may be less important than the decrease of renal plasma flow in patients with cardiac failure, since therapeutic improvement of proteinuria is more closely associated with increase in renal plasma flow than with changes in filtration rate (Lenègre et al.). Apparently, alterations in tubular protein reabsorption likewise occur.

The *fractionation of urinary proteins* by electrophoresis reveals so many individual variations in albumin and globulin fractions that in most instances of proteinuria, no characteristic pattern has evolved Differences in globulin-albumin clearance ratios remain rather small in the various renal disorders (Sellers et al ; Wolvius et al , Lewis). Possible exceptions are the relative higher ratios found in acute nephritis, in certain cases of lupus erythematosus, in pyelonephritis, and in postural proteinuria (Wolvius et al ; Squire et al.) In cardiac failure, the electrophoresis of urinary proteins does not yield any characteristic pattern (Audier et al.).

A "controlled serial protein excretion test," based upon (1) excretion rate of protein per minute (under comparable conditions), (2) duration (transient, intermittent, persistent), and (3) daily excretion pattern (continuous versus orthostatic proteinuria), has proved useful in the differential diagnosis of the various types of proteinuria (King et al ; King).

URINARY SEDIMENT

For the microscopic analysis of urinary sediments, freshly voided specimens, collected in the morning after a period of dehydration, are to be preferred. This procedure tends to yield a concentrated, acid urine, in which formed elements are best preserved (Addis). In hypotonic or alkaline urines, disintegration occurs rather rapidly, even in the bladder, and may lead to gross errors in evaluation. Addition of salt to hypotonic urine and proper acidification of alkaline urine tend to stop further hemolysis or lysis of cells and casts

nephritis in the pathogenesis of hypertension, the clinical significance of these correlations is obvious

In summary, proper examination of the urinary sediment may confirm a diagnosis, give early warning of complications, or in turn, by unsuspected findings, lead to reappraisal of the clinical picture and a change in diagnosis and therapy. When this examination is combined with visual observation of the urine and simple chemical tests, valuable information can be rapidly obtained, which amply rewards the physician's personal time and efforts devoted to these procedures.

nition and differentiation of formed elements, a supravitally staining safranin–crystal violet mixture (Sternheimer-Malbin) has found increasing use in recent years. Addition of 1 drop of the mixture to the centrifuged sediment will not only stain in distinctive fashion vaginal, bladder, and renal epithelial cells, as well as the various types of casts (for details, see recent color reproductions by Moser et al. and Schreiner, 1955), but will also reveal diagnostically significant differences in staining and morphologic appearance of *leucocytes*. They stain either violet with dark-purple nuclei and coarse-appearing, always immobile granules; or pale blue with colorless or pale-blue nuclei. In *urines of high osmolarity*, the blue cells may appear glassy with hardly discernible nuclei, while in *urines of low tonicity* they are markedly swollen with spherical or multilobulated, sometimes poorly delineated nuclei and with *slate-gray granules* exhibiting more or less marked Brownian movement ("granular motility" or "glitter" cells).

In the differential diagnosis of hypertension, *observations on stained pus cells have proved helpful in distinguishing chronic pyelonephritis from other forms of advanced cardiovascular disease.* A significant correlation between the occurrence of "glitter cells" in the urine and subacute and chronic pyelonephritis has been found by many authors (Schilling, Sternheimer et al.; Reubi et al., Goodgold et al., Talledo, Trabucco, Nieth et al., Lachnit et al., Miatello, Garcia Dardoni) but has also been disputed (Roth et al.) Although these cells are not pathognomonic, since they may also originate from vaginal pus and prostatic secretions, their appearance in larger numbers in properly collected urines appears to be highly suggestive of pyelonephritis and "may represent the best available screening test" (Schreiner, 1957) Their occurrence in chronic glomerulonephritis, noted by Schreiner, is rare (Goodgold et al; Nieth et al., Linneweh, Miatello), and, in the author's own experience, superimposed pyelonephritis is then likely to be present.

Extending these observations, an analysis was made of the occurrence in the urine of blue-staining cells irrespective of "glittering," and its association with pyelonephritis as confirmed by biopsy; a high correlation was found (Poirier et al.). Since fresh leucocytes of the blood stain blue, and only after standing turn into the dark-red-staining form, the authors suggested that in the kidney, owing to the *urine flow*, migrating leucocytes may be *excreted more rapidly* and with less alterations *than from other sites* of deep inflammation, which explained their presence in the urine in pyelonephritis rather than in association with lower urinary tract infection. They, therefore, considered the finding of pale-blue cells more *significant* than the presence of "glittering," which they stated would be of only incidental importance and predominantly due to urine osmolarity.

In this view, however, the problem of the *"glitter cell"* appears to be oversimplified *Granular motility*, the result of edema and decreased viscosity of the leucocytic cytoplasm, can occur under a variety of conditions. Aside from hypotonic media, bacterial toxins (streptococcus, staphylococcus, lipopolysaccharides) and leucocytic antibodies of immune serums are known to produce the phenomenon In vitro phagocytosis of nontoxic streptococci leaves the leucocyte intact, while that of the toxic variety induces leucocytic swelling and granular motion. Any one or all of these factors may play a role in inducing "glittering" in leu- [illegible] proteolytic effects, and altered permeability) are likely to affect not only staining but osmotic *resistance as well* By staining urinary "glitter cells" with PAS, the author has found, for instance, a very high glycogen content, verified by diastase digestion. It is evident that great caution should be used in comparing staining and osmotic behavior of blood leucocytes, already damaged by isolating procedures, with inflammatory urinary pus cells—a fact that has been all but ignored in a recent, unconvincing attempt to demonstrate their identical behavior (Schmuziger). Obviously, this problem requires further investigation

Meanwhile, it would seem appropriate that the finding of pale-blue cells or "glitter cells" in a patient's urine should invite thorough clinical examination (urine culture, renal-function studies, x-rays of the kidneys, etc). Most investigators agree that these cells are not present in essential hypertension or in noninfected urines, where leucocytes are of the red-staining variety that never shows "glittering." In view of the increasing importance of chronic pyelo-

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